# Internet Connection Method for Mobile Ad Hoc Wireless Networks

by

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# Declaration

This thesis is presented in accordance with the regulations for the degree of doctor of philosophy. All work reported has been carried out by the author unless otherwise stated.

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# Abstract


In recent years, wireless networks with Internet services have become more and more popular. Technologies which integrate Internet and wireless networks have extended traditional Internet applications into a more flexible and dynamic environment. This research work investigates the technology that supports the connection between a Mobile Ad Hoc Wireless Network (MANET) and the Internet, which enables the current wireless Internet technologies to provide a ubiquitous wireless life style.

With detailed analysis of the existing wireless Internet technologies and MANETs regarding their features and applications, the demand and lack of research work for an application to provide Internet connection to MANET is indicated. The primary difficulty for MANET and Internet connection is that the dynamic features of MANET do not suit the traditional connection methods used in infrastructure wireless networks. This thesis introduces new concept of the 'Gateway Awareness' (GAW) to the wireless devices in the MANET. GAW is a new routing protocol designed by the author of this thesis, at the University of Warwick. Based on GAW, an inclusive definition for the connection method, which supports the Internet connection and keeps the independency of routing in MANET, is addressed. Unlike other research work, this method supports the MANET and Internet communication in both directions. Furthermore, it explores possible ways of using the Internet as an extension for wireless communications.

The GAW routing method is developed from destination sequenced distance vector (DSDV) routing protocol. However, it defines a layer of wireless nodes (known as GAWNs) with exclusive functions for the Internet connection task. The layer of GAWNs brings a new set of route update and route selection method. Simulations show that the GAW routing method provides quality Internet connection performance in different scenarios compared with other methods. In particular, the connection is completed with minimum effect on the independent MANET while the routing efficiency and accuracy is guaranteed.

# Abbreviations

| | |
|---|---|
| 1G | First Generation Mobile Cellular Network |
| 2G | Second Generation Mobile Cellular Network |
| 3G | Third Generation Mobile Cellular Network |
| ABR | Associative Based Routing |
| ACIRI | AT&T Centre for Internet Research at ICSI |
| AMPS | Advanced Mobile Phone System |
| AODV | Ad hoc On-Demand Distance Vector |
| *AODV* | AODV with Reactive Gateway Discovery Method |
| *AODV-P* | AODV with Proactive Gateway Discovery Method |
| AP | Access Point |
| BGP | Border Gateway Protocol |
| BRP | Bordercast Resolution Protocol |
| BSS | Basic Service Set |
| CDMA | Code Division Multiple Access |
| CDMA2000 | Code Division Multiple Access 2000 |
| CONSER | Collaborative Simulation for Education and Research |
| CSGR | Cluster Switch Gateway Routing |
| CSMA/CD | Carrier Sense Multiple Access/Collision Detect |
| D-AMPS | Digital-Advanced Mobile Phone Service |
| DARPA | Defense Advanced Research Projects Agency |
| DSDV | Destination Sequenced Distance Vector |
| *DSDV* | Sequence Number does not Trigger DSDV Update |
| *DSDV-S* | Sequence Number Triggers DSDV Update |
| DSR | Dynamic Source Routing |
| DSSS | Direct Sequence Spread Spectrum |
| DVB | Digital Video Broadcast |
| EDGE | Enchanted Data Rate for GSM Evolution |
| ESS | Extended Service Set |
| FA | Foreign Agent |
| FHSS | Frequency Hopping Spread Spectrum |
| FM | Frequency Modulation |
| GAW | Gateway Awareness |
| GAWN | Gateway Awareness Node |
| GPRS | General Packet Radio Service |
| GSM | Global System Mobile Communication |
| HA | Home Network Administrator |
| HIPERLAN | High Performance European Radio LAN |
| IARP | Intrazone Routing Protocol |
| ICMP | Internet Control Message Protocol |

| | |
|---|---|
| IEEE | International Electronic and Electrical Engineering |
| IERP | Interzone Routing Protocol |
| IETF | Internet Engineering Task Force |
| IG | Internet Gateway |
| IGRP | Interior Gateway Routing Protocol |
| IPv4 | Internet Protocol version 4 |
| IPv6 | Internet Protocol version 4 |
| ITU | International Telecommunications Union |
| LAN | Local Area Network |
| LCC | Least Cluster Change |
| LLC | Logical Link Control |
| LSA | Link State Advertisement |
| MAC | Media Access Control |
| MACA | Multiple Access with Collision Avoidance |
| MACA-BI | MACA By Invitation |
| MANET | Mobile Ad Hoc Wireless Network |
| NMT | Nordic Mobile Telephone |
| NS2 | Network Simulator 2 |
| NSF | National Science Foundation |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OSI | Open System Interconnection |
| OSPF | Open Shortest Path First |
| OTcl | MIT Object Tcl |
| PAMAS | Power Aware Multi-access Protocol with signalling for Ad Hoc Networks |
| PDA | Personal Digital Assistant |
| PRNET | Packet Radio Network |
| QoS | Quality of Service |
| RERR | Route Error Message of AODV |
| RIP | Routing Information Protocol |
| RREP | Route Reply Message of AODV |
| RREQ | Route Request Message of AODV |
| SAMAN | Simulation Augmented by Measurement and Analysis for Networks |
| SMS | Short Message Service |
| STAR | Source-Tree Adaptive Routing Protocol |
| TACS | Total Access Communication System |
| TAPR | Tucson Amateur Packet Radio |
| TCP/IP | Transport Control Protocol and Internet Protocol |
| TDMA | Time Division Multiple Access |
| TD-SCDMA | Time Division Synchronous Code Division Multiple Access |
| TORA | Temporary Ordered Routing Algorithm |
| TTL | Time To Live |

| | |
|---|---|
| WAP | Wireless Application Protocol |
| WCDMA | Wideband Code Division Multiple Access |
| WEP | Wired Equivalent Privacy |
| WLAN | Wireless Local Area Network |
| WMAN | Wireless Metropolitan Area Network |
| WPAN | Wireless Personal Area Networks |
| WRP | Wireless Routing Protocol |
| ZRP | Zone Routing Protocol |

# Chapter 1 Introduction



## 1.1 Overview

In recent years, the developments of wireless technologies have brought us the wireless life style from personal areas to world wide communications [1]. Wireless networks offer great flexibility and mobility to users when compared with wired networks. A Mobile Ad Hoc Wireless Network (MANET, sometimes simply called an Ad Hoc Wireless Network)[2-5], which is often referred to as the infrastructureless wireless network, has become a popular research area in recent years. It is a wireless network without any central administration and established infrastructure and is to be found useful in many areas where the normal networks' infrastructures are difficult to deploy, such as military battlefields, disaster and rescue scenarios.

Current research for Ad Hoc Wireless Network carried out under the MANET charter of Internet Engineering Task Force (IETF) [6]. Recently, many routing protocols have been developed to meet the dynamic route discovery requirements for such a network. However, the current works for MANETs focused on the applications for an independent wireless domain. As wireless technologies are developing, the applications of MANETs are becoming possible in the personal communication environment with personal devices such as PDAs, mobile storage devices and laptops [7]. The applications have been extended beyond the scope of an independent Ad Hoc Wireless Network into mixed scenarios with communications between wireless and wired networks.

During the last few years, the wireless local area network (WLAN) [8] popularity has brought Internet connection to the wireless medium. It is time to consider offering connection to the Internet for MANETs, to extend the Internet application to a dynamic form. In contrast to the infrastructure wireless network, a MANET has more changeable network topologies, uncertain members, non-fixed communication channels and non-central administrations. These features decide that the Internet connection for MANETs cannot be done by simply designating an Internet Gateway (IG) as the service provider, which used to be an administrator for the infrastructure wireless network. However, since the dynamic features of MANET support infrastructureless routing within the wireless network, the connections to any destinations including the Internet can be done without the constraints of network topology. Therefore, when the Internet connection method for such a network is designed, the independency of the unique MANET needs to be considered and be extended to Internet applications.

This thesis presents a method to offer Internet connection to MANETs. The target of this work is to find a solution to support both MANET to Internet connectivity and to have the independent MANET as a stand-alone wireless network. As far as the features of the MANET are concerned, the connection service providers and their functions need to be clearly defined. Routing issues relating to the MANET requires further modifications to suit the task, which means the overall solution needs to provide Internet service with minimum effect on the routing performance in the MANET.

The method introduced in this thesis mainly covers the routing issues for MANET and Internet connection. A new concept of GAW [9] has been described for wireless nodes to achieve the research target. Based on GAW, an inclusive definition for MANET and Internet connection using GAWNs is given. A new set of routing methods with the definition of GAWNs is also developed. New functions of GAWNs to implement the connection task are clearly defined. The GAW routing method introduced in this thesis will consider not only the routing method from the MANET to the Internet, but it will also provide a way of enabling Internet nodes to gain access to the MANET. Furthermore, it also examines a possible way of using the Internet as an extension for wireless communications. The GAW routing method extends the original MANET route discovery into the Internet and provides the combination of both point-to-point Ad Hoc communication and MANET to Internet connection.

Furthermore, in Chapter 5, simulations are performed to investigate the performance of the GAW routing method on both individual functions and the overall system. Simulation results on MANET to Internet connection are analysed and compared with the other implementations. Internet to MANET communication and the extended wireless communication using GAW routing method is also discussed.

## 1.2 Motivation

This work aims to address the desire for the universal wireless life style. The development of wireless networks has changed day-to-day life providing more options in the way of communications. The great advantages of the flexibility and mobility of wireless networks have extended wireless communication services to many areas which were not possible before.

MANETs, with unique features such as no central administration and no fixed infrastructure, provide a relevantly new area, where current research work is limited in the performance inside an isolated wireless network. However, the popularity of WLANs brings the requirement to extend the MANET into a combination with both wireless and Internet services.

Considering the unique features of MANETs, the traditional way of offering Internet connection to WLAN with IG cannot be simply introduced. In MANETs, apart from using the IG to support the Internet connection, a wireless node in the Ad Hoc Wireless Network can serve the others the connection service if it gained the Internet connection. A basic design requirement is to keep the independency of MANET and the connectivity of Internet at the same time. As a result, the service provider and its functions need to be clearly defined.

The Internet to MANET communication also needs to be setup with a method to find the destinations in the MANET. Since the MANET has a dynamic topology, the members' routing information is hard to discover from the Internet without constantly probing the wireless domain. However, too much redundant data sent to the wireless network is clearly a waste of the limited network resources. As a result, an efficient method needs to be introduced to support this application.

The resources in the wireless network, such as power and bandwidth, are limited compared with the Internet. Packet forwarding in Ad Hoc routing protocols may consume significant amounts of power in these node, which are used very often. While offering the Internet connection, it is obvious that those nodes close to the Internet may carry more packets than others. This requires the connection method to be efficient with currently available resources and to use an optimal routing scheme.

A MANET with Internet connection may not only support the communication between them but also use the Internet as an extension for wireless communication. For example a route that is unavailable in the wireless network may be found through the Internet and went back into the wireless domain. This is also a way of optimising the resources in the wireless network. While the resources in wireless network are occupied, the alternative route on the Internet can be used.

All these requirements drove this research work. The GAW routing method is then developed to solve the problems and support the MANET-Internet communications.

## 1.3 Contributions to Knowledge

The research work described in this thesis contributes to the body of knowledge in the following areas:

- The idea of GAW offers the essential support to provide the Internet to MANET connection without losing the independency of MANET. The designed method separates the Internet connection process into two steps, routing in MANET and communication from GAWNs to Internet. They are connected with GAWNs and their functions are clearly defined to optimise the connection method.
- Derived from the GAW routing method, an inclusive definition is given to GAWNs as the Internet connection service provider. The definition of GAWNs manages to comprise of both access method used in the traditional infrastructure WLAN and those that can be used in the MANET.
- The GAW routing method supports communications not only from the MANET to the Internet but also from the Internet to the MANET. The defined function of GAWNs manages to achieve this target with minimum effects on wireless network.
- Based on the GAW routing method, a new extended form of wireless communication, which involves the Internet, is also introduced. This new form of communication considers the flexible routing features of MANET and the advantage of having an Internet connection to extend the traditional route discovery of wireless communication to wide discovery through the Internet.

- The concept of a GAWN layer creates a new form of route discovery in table driven routing protocols. It turns the single destination of the Internet connection service provider into a selection from a layer of multiple destinations, which includes all the available routes. By doing this, the routing efficiency and accuracy is improved.
- Essential packet distribution to support load-balancing among the available routes is introduced in the GAW routing method. The layer of GAWNs offers the opportunity for packet distribution, which minimises problems caused by varying traffic loads.

## 1.4 Outline of the Thesis

The rest of the thesis is organised in 5 chapters.

- Chapter 2 reviews the technologies in the modern wireless communication world. It takes a close look at the overall figure of the current wireless world and the application areas of MANETs, considering techniques and application issues. In addition, it explains the various wireless technologies from personal areas to worldwide applications. The relations between different wireless technologies, especially the relations of MANET with other wireless technologies, are carefully explained.
- Chapter 3 introduces the features of current Ad Hoc routing protocols, providing the essential knowledge concerning the development of Ad Hoc routing protocols for the last decade and reviewing the different routing protocols plus their special routing features.

- Chapter 4 defines the GAW routing method and its Internet connection method, offering an overall description of the GAW routing method. All the components in the GAW routing method are covered in detail and the communication forms between the Internet and MANET using the GAW routing method are also introduced.
- Chapter 5 gives the implementations and simulation results of Internet connection implementations using the GAW routing method and other methods in the NS2 simulation environment, compares and analyse the performance of the method.
- Finally, Chapter 6 draws conclusions and reviews possible future research directions.

# Chapter 2 Wireless Network Background

2.1 Overview
2.2 Mobile Cellular Networks
2.3 Wireless LANs
2.4 Wireless Mobile Internet
2.5 Ad Hoc Wireless Networks

## 2.1 Overview

In recent years, wireless communications have become pervasive in both business and personal communications. Wireless networks that offer fundamental support to wire-free communication in personal, local, metropolitan and global areas, have evolved rapidly throughout the last few decades. This chapter considers the development of wireless network technologies and their cooperation. The following sections gives a detailed description of the technologies of mobile cellular networks [10, 11], wireless LAN [12], and Mobile Ad Hoc Wireless Networks [2, 3].

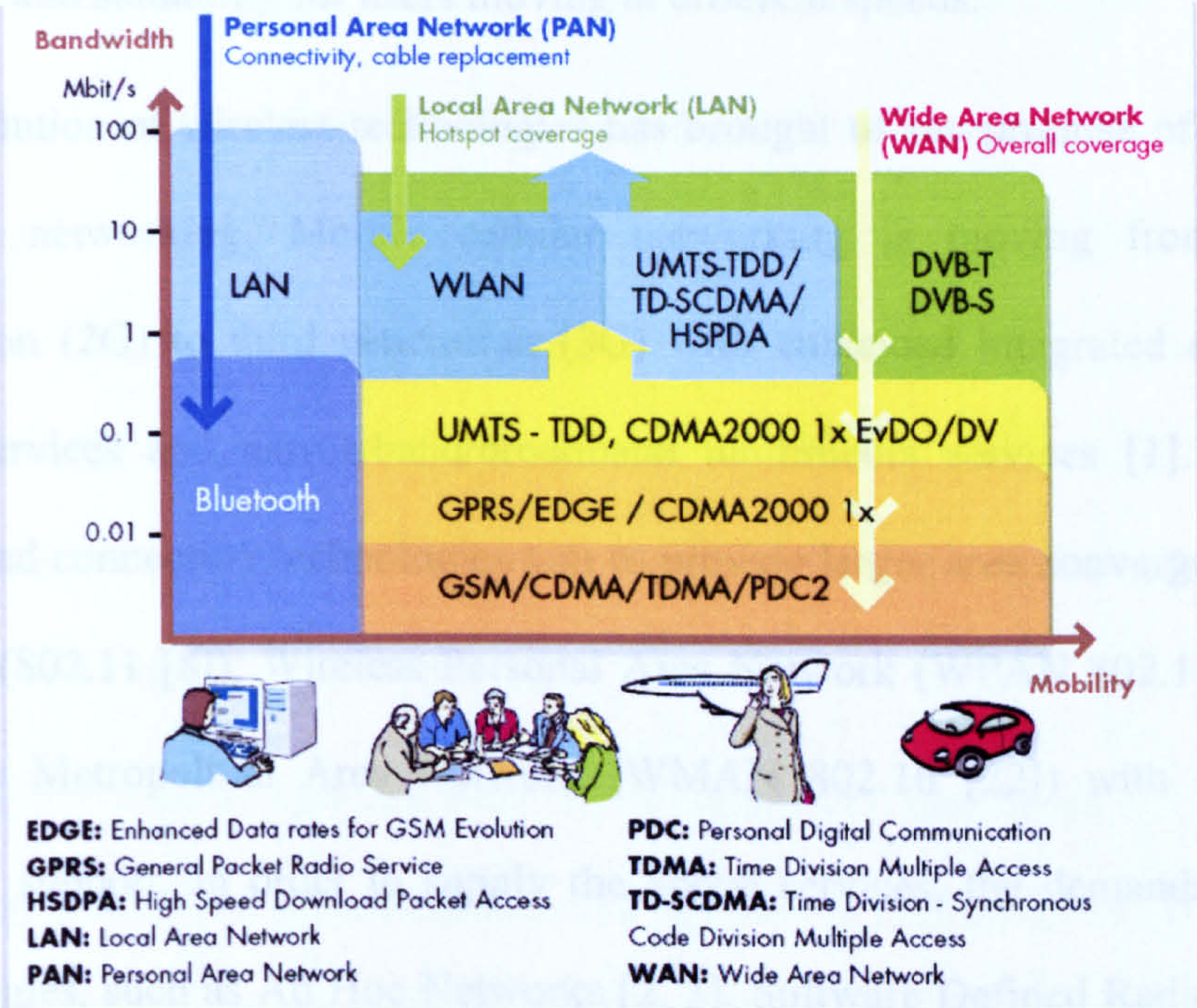



*Figure 2.1 Wireless Networks in Our Lives, Picture from [13]*

Current world wide wireless networks combine many technologies as complements of each other and have provided us with a ubiquitous wireless lifestyle. We are all experiencing the feasibility of mobile phones with the ability to have communication with others while on the move. This is the main advantage brought to us by mobile cellular networks. Wireless LAN technologies such as the IEEE 802.11 [8, 14] standards extend the Internet from the enterprise world into the public and residential domain. For example, wireless hotspots [15, 16] on campus allow us to surf online with our laptops without the restriction of having to be connected to a wired port. Other technologies such as Bluetooth [17-19] support high speed data communications at a short distance between wireless devices. In addition to these, Digital Video Broadcast (DVB) [20] technology is used for wide area broadcasting. Figure 2.1 shows the application area of various wireless technologies and how they fit into our lives with their data rate and suitability for users moving at different speeds.

The evolution of wireless technologies has brought us the promise of universal wireless networking. Mobile cellular networking is moving from second generation (2G) to third generation (3G) with enhanced integrated audio and video services and narrowband/broadband multimedia services [1]. Wireless broadband connection technologies aim to provide larger area convergence from WLAN (802.11 [8]), Wireless Personal Area Network (WPAN 802.15 [21]) to Wireless Metropolitan Area Network (WMAN 802.16 [22]) with additional mobility support. In order to supply the above services, the demands for new technologies, such as Ad Hoc Networks [2, 3], Software Defined Radio [23-25], Ultra Wideband [26, 27] and Intelligent Networks [28] are increasing. The technology introduced in the thesis is developed to support the true wireless Internet for Mobile Ad Hoc Wireless Networks.

## 2.2 Mobile Cellular Networks

Mobile cellular networks play an important role in our day-to-day life. Recently in the UK, and many other parts of the world, people are experiencing the above-mentioned evolution of 2G to 3G wireless systems. This section gives a brief introduction to this mobile cellular network evolution process.

The first generation (1G) wireless networks were designed to provide voice and low data rate communications. They are also called the analogue cellular system since they provided analogue transmission services. The 1G systems used Advanced Mobile Phone System (AMPS) [29], Total Access Communication

System (TACS) and Nordic Mobile Telephone (NMT). Frequency Modulation (FM) was the technique for radio transmission used in this generation.

2G protocols include GSM (Global System Mobile Communication) [30], D-AMPS and Code Division Multiple Access (CDMA) (IS-95) [31]. The most significant change in the second generation is the use of the digital multiple access technologies TDMA (time division multiple access) and CDMA. 2G networks are currently used around the world supporting voice, paging, fax and the short message service (SMS).

In 2G mobile cellular systems, only limited data communications are supported. The features provided by broadband, such as multimedia transforms with Quality of Service (QoS) assured services, are the primary target of the design of 2.5G and 3G mobile systems. General Packet Radio Service (GPRS) [32, 33]was developed for GSM networks adding packet-switching protocols, shorter setup time for ISP connections, and the possibility to charge the user by the amount of data sent rather than connection time. A significant contribution in 2.5G is Enhanced Data Rate for GSM Evolution (EDGE) [34], which makes the offering of wireless multimedia IP-based [35] services possible over the GSM network.

The third generation mobile systems offer broadband service to wireless users. Services with good QoS assurance become possible in 3G. The ITU (International Telecommunications Union) introduced the 3G framework IMT2000 [36], with the aim of supporting high-speed access, broadband multimedia services and universal mobility. The standard protocols for 3G are Wideband CDMA (WCDMA), CDMA2000 and Time Division Synchronous - CDMA (TD-SCDMA) [37, 38].

*Table 2.1 The Three Generations of Mobile Cellular Networks*

| Mobile Cellular Networks | Transmission | Standard Protocols | Services |
|---|---|---|---|
| First Generation | Analogue | AMPS, TACS, NMT. | Voice and low data rate data communications. |
| Second Generation | Digital | GSM, CDMA (IS-95). | Voice, paging, fax and short message service. |
| Third Generation | Digital | WCDMA, CDMA2000, TD-SCDMA. | High speed access, broadband multimedia service, universal mobility |
| Beyond 3G | Digital | Not released yet. | More bandwidth, real time multimedia transmission and seamless convergences. |

As the world is moving from 2G to 3G mobile cellular networks, the definition of network beyond 3G networks or 4G networks is becoming an issue. There are currently no clear definitions of 4G but it is expected to have much more bandwidth, real time multimedia transmission and seamless convergences. Table 2.1 shows the different generations of mobile cellular network. More information regarding networks beyond 3G is discussed in [13, 39, 40].

## 2.3 Wireless LANs

### 2.3.1 Overview

As the 3G mobile cellular networks aim to offer broadband services to cover the long distance voice and data communications, Wireless LANs (WLANs) [12] are more and more in demand to provide the "last mile" data services to the users with wireless enabled devices. WLANs are mostly based on the Ethernet media access technology and act as an extension to the local wired network. Traditional ways of networking with Ethernet technology have reduced user mobility with the inconvenient and expensive deployment of wired cable. Wireless LANs, with the application of wireless connectivity, have no such restriction and provide considerably more free movement for the users. The two primary standards in the world for WLANs are IEEE802.11 in the United States and HIPERLAN (High Performance European Radio LAN) [41] in Europe.

Current wireless LAN technology offers several fundamental advantages to users, of which the first is the feature of mobility for wireless networking. A user in a wireless network can easily connect to existing networks and roam between networks without the constraint of cabling. One example is the wireless hotspot service on an education campus. Equipped with a wireless network card, the user can access the Internet service in the library, in a café or even on a chair beside the lake, given sufficient numbers of access points.

Another advantage of wireless networks is flexibility, which allows such a network to be quickly deployed. Without wires, the network can be deployed in some difficult areas where the wired network is not applicable. Normally wireless networks have several base stations to connect the users to the existing network. As a new user joins, no infrastructure changes to the network are needed but only a security check to ensure authorization from the base station. The authorization process involves a configuration of the network to provide the service to the new user. Since this process does not ask for any infrastructure changes, the wireless network can be deployed much more quickly [14, 42].

### 2.3.2 Wireless LAN Topology

The network topology of a wireless LAN can either be a fixed infrastructure or infrastructureless (Ad Hoc). Wireless LANs with a fixed infrastructure normally have at least one base station node that manages the network traffic as an administrator to provide synchronization and coordination for all the member nodes. The base stations with wired connection extend wired networks into wireless domains.

An infrastructureless (Ad Hoc) wireless LAN is a network without any central administration. The Ad Hoc network is a group of independent wireless nodes communicating on a peer-to-peer basis [43]. All network members move around making the network topology change from time to time. It is called infrastructureless because the network topology changes frequently and given the fact there is no central administration, the wireless nodes in Ad Hoc networks have to communicate with each other through self-organised channels.

These two types of wireless LAN are used more and more today and are becoming the complement of each other, to offer seamless convergence. Infrastructure WLANs offer an access service to wired LANs through the use of base stations. Each base station administers one cell and provides wired network access to all the nodes within its coverage. By employing frequency reuse schemes in a cellular structure, the total available bandwidth of a system can significantly increases. An Ad Hoc WLAN is suitable for a situation where a temporary or emergency wireless LAN is needed. It can be deployed quickly without any base station needing to be present.

### 2.3.3 Types of Wireless Communication

According to the network topologies, wireless communications in WLAN also have different types. In the wireless network with a fixed infrastructure, the base stations are the administrators of the networks. As a result, communications between each wireless node have to go through one or more of the base stations. It is obvious that the wireless nodes must be within the radio range of base stations in order to send and receive data. The base stations handle all the communication requests from the sources and forward them to the destinations directly or through other base stations. Handovers between base stations provide wireless users with seamless communication between the networks when the user is on the move. Mobile cellular networks are also using this form of communication.

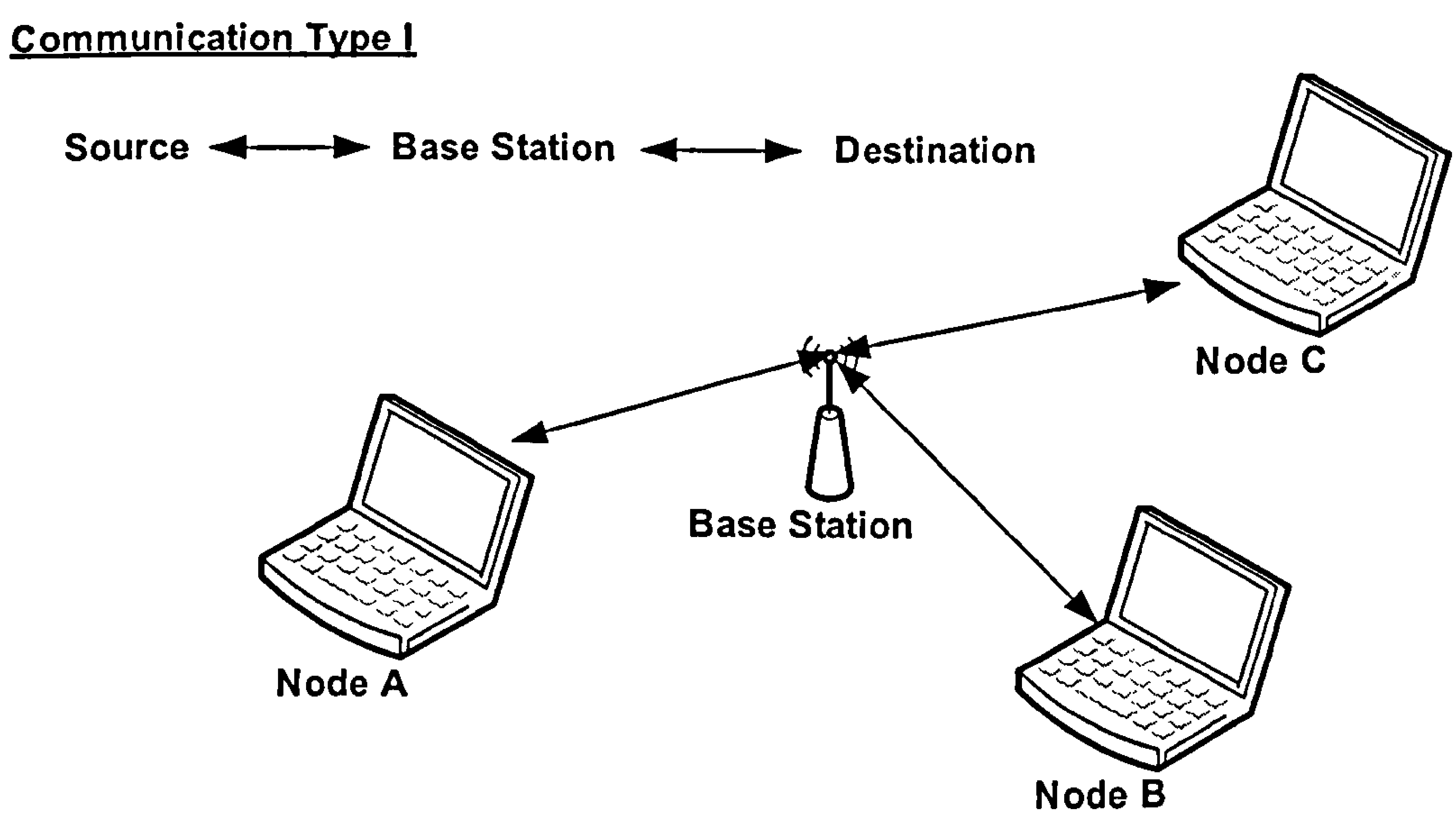



*Figure 2.2 Wireless Communication Type I*

Being used in fixed infrastructure networks, this communication type is limited to the channel of source->base station/base stations->destination. Also the wireless nodes do not have a routing scheme and peer to peer communication ability. As a result, two wireless devices cannot communicate with each other if either of them are out of the coverage of a base station and even if they were within the reach of each other. Figure 2.2 shows the central administration of base station and the communication type.

Another mode of communication is used in Ad Hoc Wireless Networks, known as peer-to-peer communication. In this case, the wireless nodes can communicate with their immediate peers. The communication can start between any two wireless nodes as long as they are within the radio range of each other. Additionally, when source and destination are more than one hop away, they can still communicate with the intermediate nodes to forward the source's packet. The wireless nodes that can carry out the peer-to-peer communications must work as both terminals and routers.

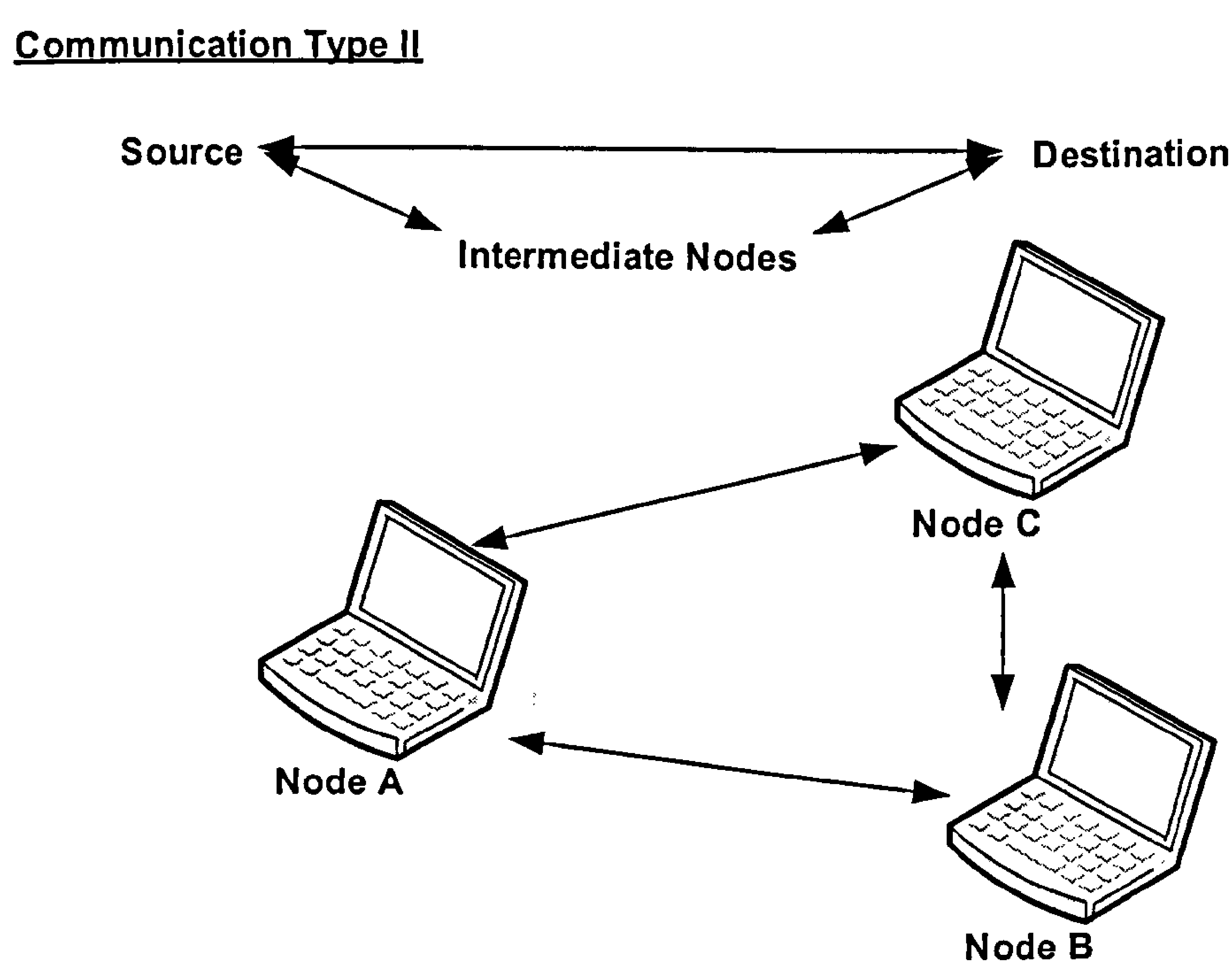



*Figure 2.3 Wireless Communication Type II*

Peer-to-peer communication is developed to be the complementary communication form in infrastructure wireless networks. For example, mobile phones with Bluetooth technology offer normal cellular communications as well as peer-to-peer communication with another device which has a Bluetooth port. Figure 2.3 shows the communication in a peer to peer mode.

## 2.3.4 IEEE 802.11 Family

In 1997, the IEEE standardised the 802.11 [8] protocols to support wireless media access. The specification defined the necessary framework for wireless LAN communications. Since the standards are compatible with Ethernet, there is no protocol conversion is needed. IEEE 802.11 uses the 2.4GHz unlicensed band to provide network speed up to 2Mbps using either of two spread spectrum encoding schemes [44, 45]: Frequency Hopping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS).

IEEE 802.11a [46] was ratified on Sept 16 1999. It uses the 5GHz band and provides a much faster data rate (up to 54Mbps), via the encoding technology Orthogonal Frequency Division Multiplexing (OFDM) [47]. These specifications make 802.11a operate with significant faster data rate and interference free on 5GHz band. However, international use of the 5 GHz band and the cost of operating at such a high frequency are challenges to the 802.11a.

The IEEE 802.11b [48] specification came out at the same time as 802.11a but the products of 802.11b came to market much earlier than 802.11a. It has become the 'de facto' wireless networking standard over the last few years. Operated at 2.4GHz, it offers excellent coverage compared to the 802.11a with the same power and gain. Using DSSS, the 802.11b user can select the best rate from 1, 2, 5.5 or 11Mbps. As a result, the 802.11b become the most suitable wireless standard for general use in the market.

The latest standard the 802.11g [49] uses the OFDM encoding scheme of the 802.11a in the 2.4GHz band. To make itself compatible with the 802.11b, it can roll back to DSSS encoding. Theoretically, the 802.11g can achieve a data speed of 54Mbps in the 2.4GHz band and still be able to maintain compatibility with the existing 802.11b. With all these promising aspects, the 802.11g is likely to become the next ubiquitous wireless technology.

Other standards in the 802.11 family have been developed, including the 802.11f [50], 802.11e [51] and 802.11i [52]. The 802.11f (Inter-Access Point Protocol) works to support wireless user roaming from one access point to another. The 802.11e (Media Access Control enhancements for QoS) adds extra functionality to the 802.11 Media Access Control (MAC) layer to improve QoS for better support of a larger set of applications. The 802.11 [8] uses Wired Equivalent Privacy [53] (WEP) to provide security for WLANs. The 802.11i (MAC enhancements for security in the 802.11) specifies the use of relatively weak, static encryption keys without any form of key distribution management.

## 2.4 Wireless Mobile Internet

### 2.4.1 Overview

From the evolution path of mobile cellular networks and wireless LANs technology, the target of anytime, anywhere data communication is becoming possible. WLANs are deployed by mobile operators around the world with the aim of offering seamless mobility with cellular networks. Shown in Figure 2.4, several technologies have now provided the wireless Internet to all wireless users with different types of communication including data, video, and voice [54, 55]. A brief overview of the relevant technologies will now be given.

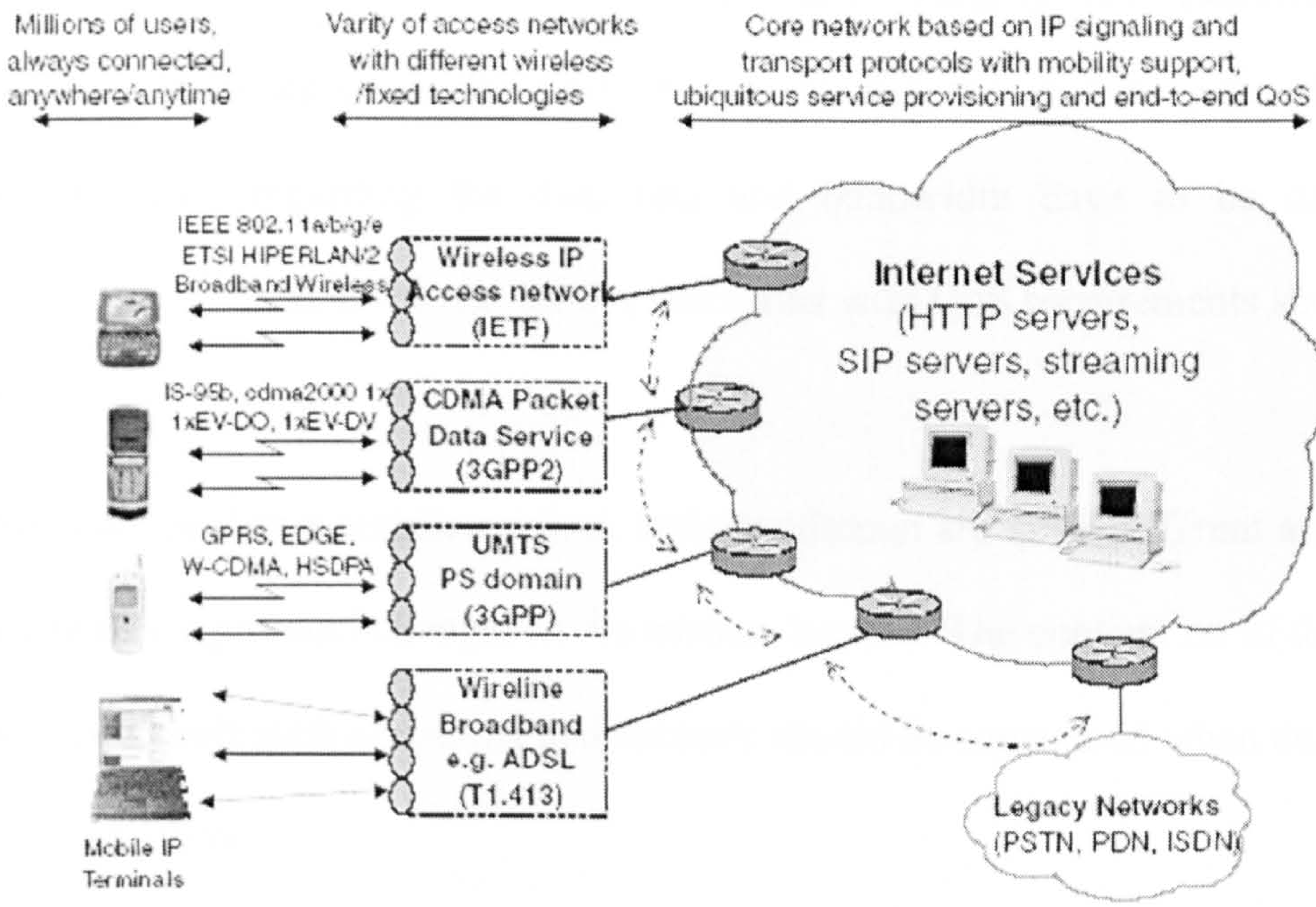



*Figure 2.4 Wireless Internet Applications, Picture from [54]*

The wireless mobile Internet is an integration of Internet and telecommunication technologies. It allows mobile users gain access to Internet services as they are on the move. New technologies in hardware design, software applications, routing and address protocol design are making the mobile Internet a comprehensive technology.

## 2.4.2 Wireless Internet Requirement

The requirement for wireless mobile Internet is to smoothly extend the normal Internet with mobile features. This extension should be seamless from a fixed domain to a mobile domain. First, the connection to the Internet should not be interrupted while the wireless user is moving between the two domains. Second, the Internet service should stay independent of the access technology used by the wireless network.

While providing the Internet connection, the mobile Internet network demands the quality of service maintained at an acceptable level [56]. This QoS should not change significantly as the user moves around the mobile network. The specifications regarding the data rate and bandwidth have to be carefully examined. A demand for real time applications with QoS requirements should be met.

Protocols used in a mobile network and the Internet are quite different and there is a need for protocol changes in the mobile Internet. The convention of different layer protocols such as routing and security should be considered when designing the connection.

When the service covers both the Internet and the mobile wireless network, security becomes an important issue. The wireless network does not provide the same level of authorisation and security service as the Internet. Users' authentication and authorisation need to be done before they reach the Internet services. Information sent to the mobile wireless network needs a wireless security protocol to remain confidential.

By managing the network resources, such as bandwidth, power, energy and congestion control, the wireless Internet should provide an optimised and reliable service to all the users present in the network.

### 2.4.3 Internet and TCP/IP

While talking about the wireless mobile Internet, it is necessary to know a little about the current world wide Internet. The Internet is a specific worldwide network of TCP/IP systems [57, 58], developed from the original ARPAnet and other research networks. Currently the Internet consists of many private and public networks that offer a multi-layer network design. It is most commonly known by its useful and powerful network layer and transport layer, which support host-to-host communications using the TCP/IP protocols. However, TCP/IP is not a single protocol but rather a collection of protocols that cover the range from application functions such as web browsing, to the low-level network protocols like IP [59, 60]. In what follows, a brief introduction to the network protocols in TCP/IP will be given.

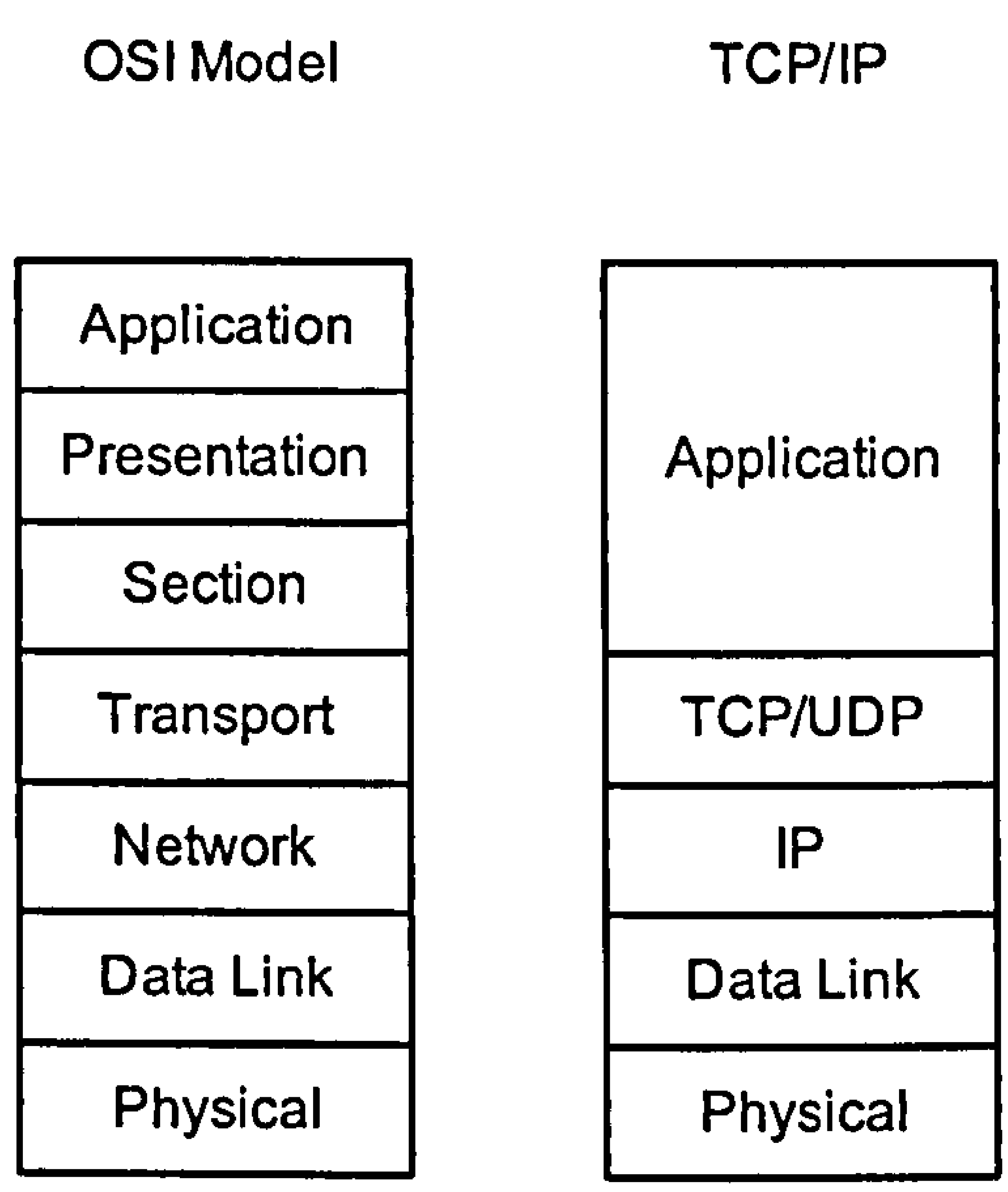



*Figure 2.5 OSI and TCP/IP Protocol Stacks*

Figure 2.5 shows a comparison between the TCP/IP protocol stack and the Open System Interconnection (OSI) [61] protocol stack. As a standard layer network system definition, the OSI model defines 7 layers in the network system, physical layer, data link layer, network layer, transport layer, secession layer, presentation layer and application layer. Each layer has a clearly defined function. The OSI model sets up a layered framework for the design of network systems that allows for communication across all types of computer systems. The TCP/IP suite is designed before the OSI model and is the de facto standard for networking. There are only 5 layers in the TCP/IP suite and they do not correspond exactly to the OSI layers. The lower four layers are the same but the fifth layer in the TCP/IP suite is equivalent to the combined session, presentation and application layers of the OSI model.

In almost all networks, the network layer plays an important role at devices such as end hosts, routers and bridges. It is sometimes referred to as the IP layer because of the usage of the Internet protocol at this layer for the Internet. IP is the most widely used protocol among the internetworking protocols at the network layer. The sessions of the network layer [62] actually include the internet protocol, routing protocol and internet control message protocol (ICMP). IP is responsible for network addressing conventions, datagram formatting and packet handling conventions. The routing protocols select the path for each packet in the network using routing [63]. In the Internet, the common routing protocols are RIP (routing information protocol [64, 65]), OSPF (open shortest path first [66]), IGRP (interior gateway routing protocol [67]), and BGP (border gateway protocol [68, 69]). ICMP [70] is used for error reporting and router signalling in the network layer.

### 2.4.4 Wireless Ethernet

When the mobility of wireless users is low and within a local scale, wireless LAN technology will satisfy the needs of an Internet connection. The current IEEE 802.11 family standards are compatible with Ethernet so that the wireless users can access the local wired Ethernet services without the problem of protocol conversion. As a result, the IEEE 802.11 wireless standard is commonly referred to as "Wireless Ethernet" [14] (Figure 2.6).

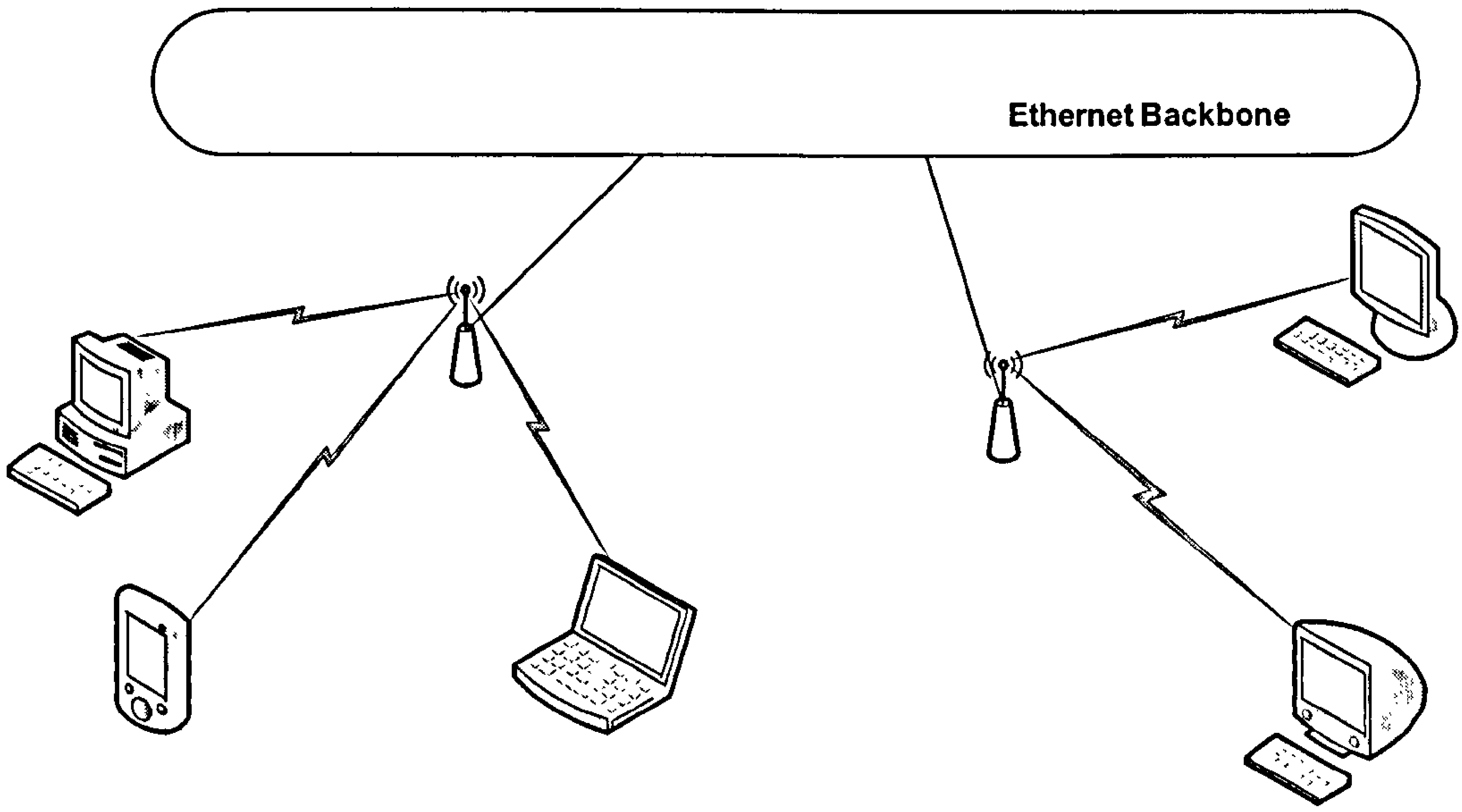



*Figure 2.6 Wireless Ethernet*

Defined by IEEE 802.11, wireless nodes in the independent BSS (basic service set) establish MAC layer wireless links with the other devices in the same BSS to setup the communication channel. The frames are transferred directly from sources to destinations. This means that to communicate between wireless nodes, the nodes in an independent BSS must be within radio range of each other. Currently, no architectural provisions are made for connecting the independent BSS to an external network. All the communications are limited within the independent BSS.

IEEE 802.11 supports the external network connection for another type of BSS which is the infrastructure BSS, commonly used to extend the connection between wireless and wired networks. Within each infrastructure BSS, a special central device called an access point (AP) is defined. APs have fixed locations and channels to the wired network. Wireless nodes in an infrastructure BSS establish MAC layer links with an AP and only communicate to and from the AP. As a result, wireless nodes can communicate with another node through the AP(s) even though they are not in the direct range. An ESS (extended service set) with multiple APs allows wireless LAN connectivity to be offered over a large extended area.

APs bridge between IEEE 802.11 wireless LANs and IEEE 802 wired LANs and construct extended wired and wireless 802 LAN networks. By using this technology, the service normally offered by wired LANs is available to wireless nodes with good mobility support.

### 2.4.5 Mobile IP

In recent years, the number of wireless devices supporting IP has rapidly increased from personal computers to personal digital assistants and even cellular phones. The use of IP addressing brings the problem that the IP address may not be the same when the wireless devices move from one network to another. However, whether the wireless devices connect to the network from a fixed location or from a dynamic one, it would be good to keep the same identity so that other devices can reach them at the same IP address. Since TCP is an end-to-end protocol, it is also necessary that the TCP end host keeps the same IP address during one session.

To handle the problem, Mobile IP [71] is defined to support IP mobility, and uses the concept of mobility agents with two different types of address. In the network in which the mobile host normally resides, the mobile host is assigned a home address, where it can always be reached. The home network administrator (HA) gives the mobile host this address. If the mobile host moves physically to another network, the IP address it uses needs to be changed. Another mobility agent, which is usually a router in the foreign network, can act as a foreign agent. A new care-of address is given to the mobile host as a temporary IP address to use in a foreign network. The home agent and the foreign agent (FA) now handle the transmissions intended for the mobile host.

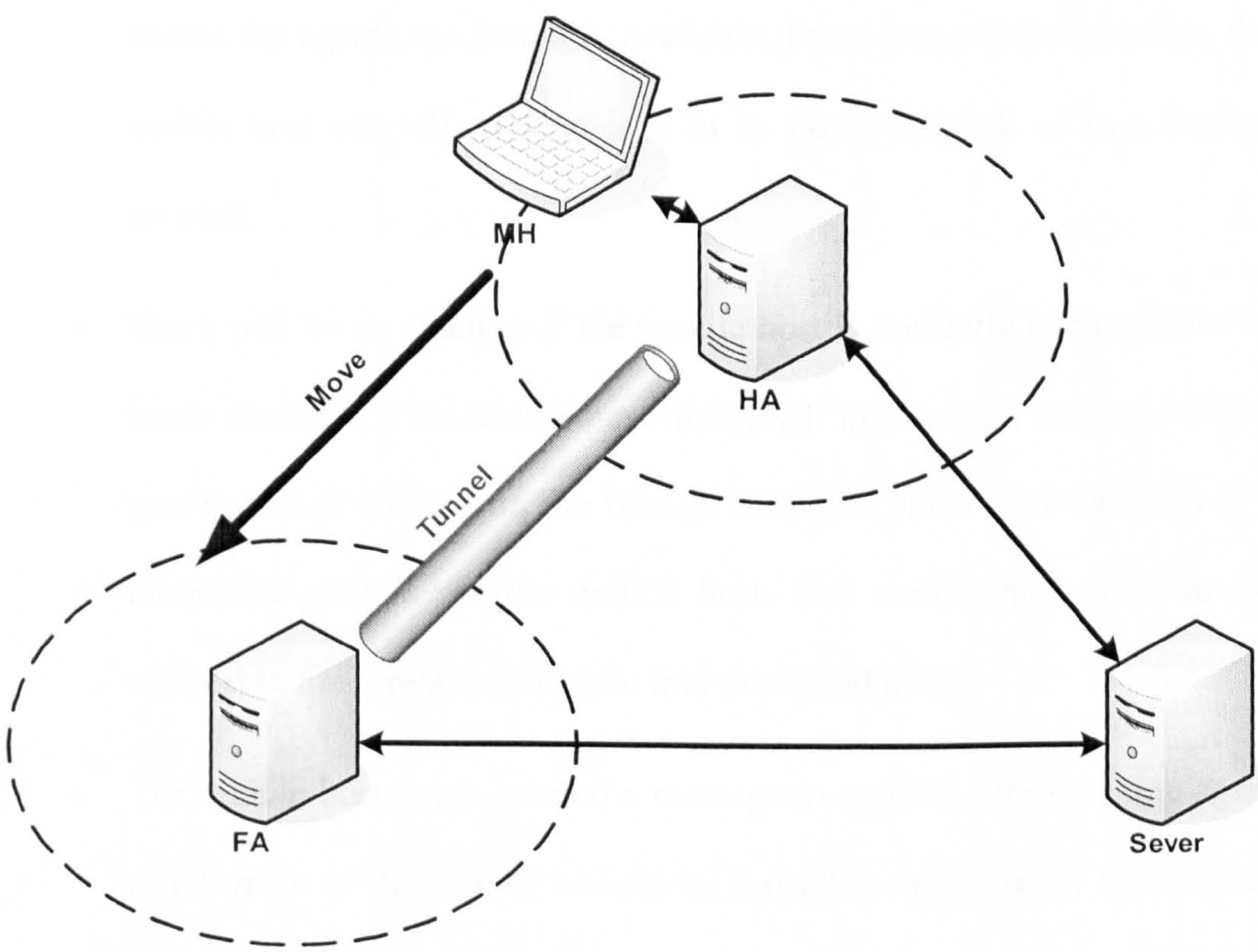



*Figure 2.7 Mobile IP*

By defining the home address and the care-of address, Mobile IP considers the mobility problem in the IP networks as a routing problem. The HA and the FA are employed to handle the issue of how to route the packets to a host's address correctly when it is in a foreign network and how this host can send packets using a new foreign network resource. Using an appropriate routing mechanism, Mobile IP provides a solution for handover between networks.

When a mobile host is away from its home network and in a foreign network, Mobile IP uses the following steps to build up the connection.

- Both foreign agent and home agent send out periodical advertisements to the wireless network. The mobile host receives these messages and knows the agents are currently available. From these advertisements, the mobile host can tell whether it is in its home network or in a foreign network.

- There will be no changes if the mobile host is currently connected to its home network. If the mobile host finds itself in a foreign network, it then gets a care-of address on the foreign network. This care-of address is a temporary address for the mobile host. The mobile host now can be reached in the foreign network at this care-of address.

- The mobile host needs to send a message to register with its home agent to inform it of the care-of address so that all the packets for the original home address can be forwarded to the care-of address.

- Once the home agent gets the care-of address, it encapsulates the packets to the mobile host in an IP tunnel directed to the care-of address. If the care-of address is allocated by the foreign agent, it can be unwrapped by the foreign agent and forward it. If the care-of address is a separate IP address specially assigned to the mobile node on the foreign network, the mobile host receive the packets and unwrap it by itself.

Nothing needs to be done when the mobile host sends packets on a foreign network. It can use the home address as the source address for the packets and has no need to worry about it. Figure 2.7 summarises the arrangement.

## 2.5 Ad Hoc Wireless Networks

### 2.5.1 Overview

An Ad Hoc Wireless Network is a network with wireless devices forming and functioning without any central administration and established infrastructure. Therefore, Ad Hoc wireless devices must be able to detect the presence of other devices in order to form such a network on the fly. In Ad Hoc Wireless Networks, wireless devices can communicate with other devices within, or indeed outside of, their radio range in a self-organised form. To support such communications the wireless devices in Ad Hoc Wireless Networks need to serve as both terminals and routers so that they can forward the data packets from the source to the destination.

The applications of Ad Hoc Wireless Networks can be found in many places. Since they do not need any established infrastructure, they can be deployed rapidly. The use of Ad Hoc wireless networks can be found in the area where normal network infrastructure is difficult to deploy such as military battle fields, disaster and rescue scenarios. As the wireless technologies are developing, the applications of Ad Hoc wireless networks are becoming possible in the personal communication environment with personal devices such as PDAs, mobile storage devices and laptops.

The original idea of having an Ad Hoc wireless network started in 1970s with the DARPA project named packet radio network (PRNET) [72]. Packet radio was a technology that extended the concept of packet switching to the domain of broadcast radio network. The PRNET system consisted of several mobile radio repeaters, wireless terminals and the mobile stations. Once installed, the system was self-initialising and self-organising. The network members did not need any administration and should be able to discover the radio connectivity among the nodes. The difference between packet radio networks and Ad Hoc Wireless networks is that the node's mobility in a packet radio network is not very high. However, as microelectronic technology develops, nodes in Ad Hoc Wireless Network can move freely, resulting in a highly dynamic topology. New technologies are being developed to support high mobility networks.

Currently, the IEEE 802.11 standards for WLANs and the Bluetooth specifications for short range wireless communications have emerged for Ad Hoc Wireless Networks. The IEEE 802.11 defines the ad hoc mode which provides the platform for peer to peer communication. It is expected to have a total coverage of several kilometres with the deployment of 802.11 WLAN. Bluetooth technology can be used to build Ad Hoc Wireless Networks in a personal area. There are mobile devices in the current market, such as PDAs and laptops, which connect personal devices in the range of 10 meters up to 100 meters [73].

Ad Hoc Wireless Networks are the subject of considerable research. Mobile Ad Hoc Networking (MANET) [5] is the name of an international working group in the Internet Engineering Task Force (IETF) and serves the goals of introducing MANET routing specifications to the Internet Standards. In the following sections, some contributions from MANET group regarding the routing in Ad Hoc Wireless networks will be introduced. (The term - MANET will be used instead of Ad Hoc Wireless Network from this point onwards.)

### 2.5.2 MANET Protocol Stacks

This section presents the protocol stacks of MANETs. In order to compare it with the OSI model and TCP/IP model, a similar layered MANET is shown in figure 2.8. The idea of a conversional layer structure of a MANET is also discussed in this section.

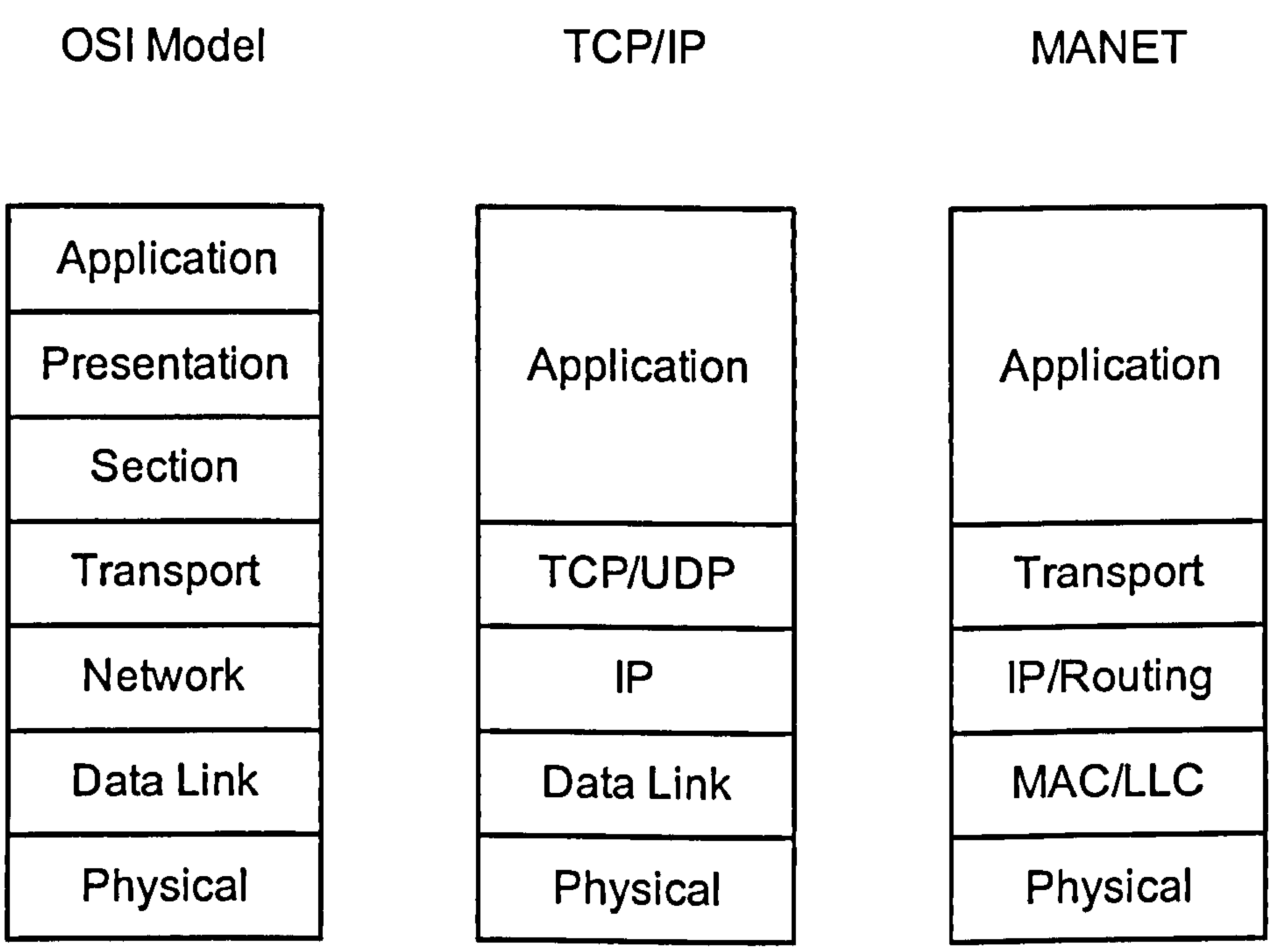



*Figure 2.8 OSI, TCP/IP and MANET Protocol Stacks*

The MANET protocol stacks are defined similarly to the TCP/IP suite with 5 layers. In the physical layer, mobile nodes run protocols that have been designed for wireless channels, such as IEEE 802.11 and HIPERLAN 2. Other technologies such as Bluetooth can also be employed. In the data link layer, both the MAC and the LLC are defined. The CSMA/CD used by IEEE 802.11 can be used in this layer. Other MAC protocols such as MACA [74], MACA-BI [75, 76], and PAMAS [77], are being developed for MANETs.

Unlike the nodes in the TCP/IP network, MANET nodes are both hosts and routers. As a result, in the network layer, MANET nodes use the Ad Hoc routing protocols to allow the nodes to forward data packets to the destinations. The network layer also employs the IP protocol. Both IPv4 and IPv6 [78] reserve a prefix for MANET. Ad Hoc routing protocols will be more fully discussed in Chapter 3.

In the transport layer, some modifications have to be made to fit TCP into MANETs. The reason is that the method TCP uses to maintain the route does not suit the frequently changed MANET topology where lots of links break. In the application layer, some application protocols such as WAP [79] can be used for data services.

In some recent research [80-82], cross layer design has been considered for MANETs. The cross layer design lets protocols that belong to different layers cooperate in sharing network status information while still maintaining the layers' separation at the design level. The method using cross layer design can optimise the energy management. It is being considered to be a new architecture to improve the performance of MANET. Cross layer design method is not used in this thesis, however, it could be employed in future work.

### 2.5.3 Internet Connectivity for MANET

A stand alone MANET is useful in many cases. Apart from having a highly flexible MANET, it is worth thinking of involving the Internet connection for it. If a node in an MANET also has connectivity to the Internet, it is advantageous for that node to offer this to other nodes.

Considering the network topology to offer this connectivity, one method is to set up base stations with wired connections in the MANET. These base stations do not administer the communication within the network like the base station in an infrastructure network but act only as a gateway to the Internet. As a result, the wireless nodes can still have peer to peer communications between each other and only the request to Internet communication will be forwarded to the base stations and on to the Internet. This method retains the independence of having a MANET without the constraint of base stations and extends the Internet service to the wireless network at the same time.

Alternatively, if a wireless node in the MANET gains Internet access, it can become the gateway node and offer a connection service when other users desire Internet access. A laptop computer with both wireless and wired interface is a good example of this type of wireless device.

No matter which approach is used, given the different features concerning routing issues of the networks, both methods demand further development of the current Ad Hoc routing protocols.

### 2.5.4 Some Research Work on MANET Internet Connection

In the past few years, considerable work has been performed on routing protocols for MANETs but only a few issues have been investigated in the field of providing them with Internet connectivity. One solution presented in 'MIPMANET-Mobile IP for Mobile Ad Hoc Networks' [83] used Mobile IP to provide the connectivity. In this work, the mobile node that needs Internet connection registers with the foreign agent first and tunnels all packets to the registered foreign agent. After the registration, the foreign agent can encapsulate the packets and forward then to destination. The Ad Hoc routing protocol AODV [84, 85] is used to deliver the packets between foreign agent and mobile nodes. Another piece of work, which involved Mobile IP and AODV, is 'Global Connectivity for IPv4 Mobile Ad Hoc Networks' [86]. In this Internet draft the discovery mechanism for foreign agents in Mobile IP is discussed.

There are also some approaches that do not use Mobile IP. In 'Wireless Multihop Internet Access: Gateway Discovery, Routing and Addressing' [87] the gateway discovery issues are discussed with different routing methods. The Internet draft 'Global Connectivity for IPv6 Ad Hoc Wireless Networks' [88] describes the method to implement the Internet connectivity for MANET. It discusses how a mobile node and base station should operate. The draft also uses a reactive routing protocol to explain some issues including gateway discovery method and modifications on route discovery messages. The master's thesis 'A study of Global Connectivity for Ad Hoc Wirelesses networks' [89] implemented the method introduced in the draft and the results from it are later compared with the routing method developed in Chapter 5.

# Chapter 3 Ad Hoc Routing Protocols



## 3.1 Ad Hoc Routing Protocols Overview

The traditional routing protocols [63] for wired networks use distance-vector and link state to maintain the routes map for all the destinations. Link state protocols are based on the distributed map concept: all nodes have a copy of the network map, which is regularly updated. When a network link changes state (up to down, or vice versa), a link state advertisement (LSA), is distributed throughout the network. All the routers note the change, and re-compute their routes accordingly. Distance vector protocols require that each router simply inform its neighbours of its routing table. For each network path, the receiving routers pick the neighbour advertising the lowest cost, and then add this entry into their routing tables for re-advertisement.

The mobility of wireless users and dynamically formed network topologies cause a big problem for implementing the routing scheme for MANET. The traditional distance-vector and link state routing protocols are unable to catch up with frequent link changes in the network. In recent years, many Ad Hoc routing protocols have been developed. Shown in Figure 3.1, these protocols may generally be categorised as table-driven, or source-initiated. In this chapter, several Ad Hoc Routing Protocols will be introduced.

Table-driven routing protocols use a proactive scheme to maintain up-to-date routing information for every node in the network. Each node maintains routing tables with route information. In order to keep up to date with the network topology changes, all network members wait for the propagation message from its neighbours and make responses accordingly. Examples of table driven routing protocols are DSDV [90] WRP [91], STAR [92] and CSGR [93]. DSDV is described in 3.1 and CSGR is described in 3.2.

Unlike table-driven routing protocols, on-demand routing protocols do not maintain any routes beforehand but intend to discover them when necessary. These protocols use a reactive scheme to create a route only when there is a need for communication between nodes. The desired routes are set up and maintained until the communication is finished or the route itself becomes unavailable due to network link changes. Examples of on demand routing protocols are AODV [84, 85], DSR [94], TORA [95] and ABR[96]. AODV and DSR will be described in 3.3 and 3.4 respectively. The on demand protocols do not use periodical routing advertisement messages, reducing the network bandwidth overhead, particularly during periods when little or no significant host movement is taking place. Battery power is also conserved on the mobile hosts, both by not sending the advertisements, and by not needing to receive them.

In addition to the above categories, it is possible to adopt a hybrid approach, where nodes proactively maintain link information for nodes within a variable-sized local neighbourhood, whilst reactively sending out route queries distant destinations. The hybrid routing protocol ZRP [97] will be discussed in 3.6.

A new routing method, GAW routing method, which is developed from DSDV will be introduced in Chapter 4.

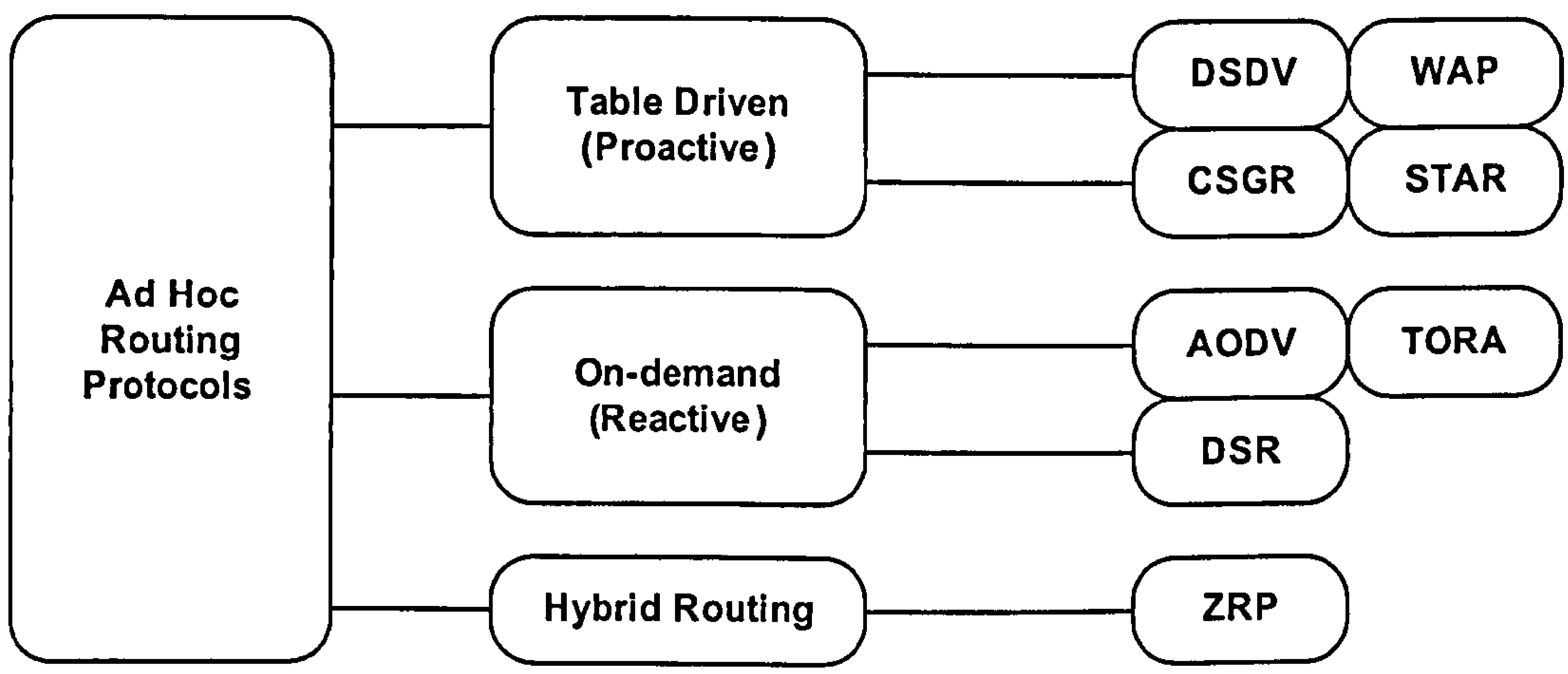
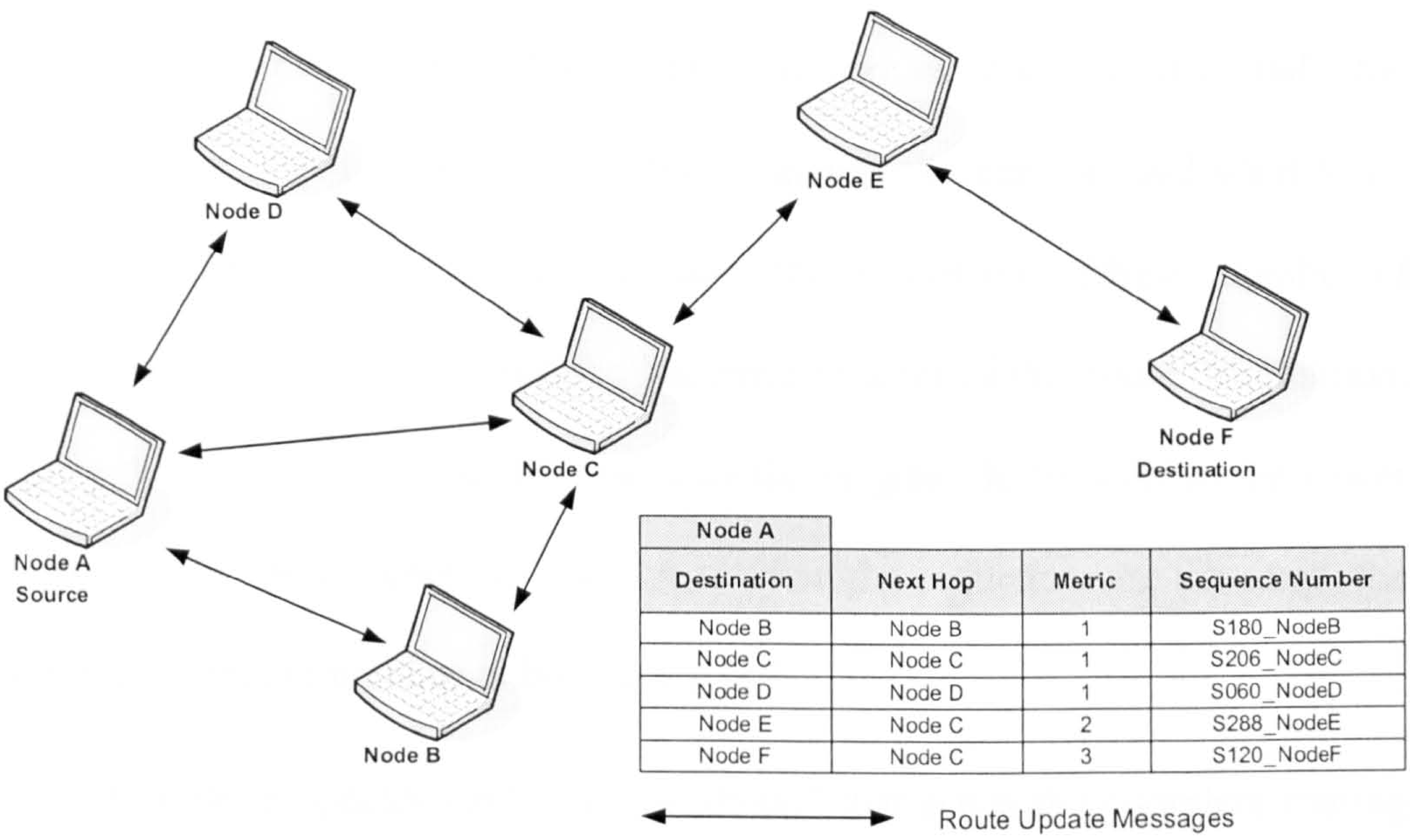



*Figure 3.1 Ad Hoc Routing Protocols*

## 3.2 Destination Sequenced Distance Vector

DSDV is a proactive routing protocol based on the idea of the classical Bellman-Ford Routing Algorithm [98], with certain improvements. Every mobile node maintains a routing table that lists all available destinations, the number of hops to reach each destination, and the sequence number assigned by each destination node. The sequence number is used to distinguish stored routes from new ones. Figure 3.2 shows an example of the route update process and the routing table on a node.




| Node A | | | |
|---|---|---|---|
| Destination | Next Hop | Metric | Sequence Number |
| Node B | Node B | 1 | S180_NodeB |
| Node C | Node C | 1 | S206_NodeC |
| Node D | Node D | 1 | S060_NodeD |
| Node E | Node C | 2 | S288_NodeE |
| Node F | Node C | 3 | S120_NodeF |

*Figure 3.2 DSDV Route Update and Routing Table*

## 3.2.1 Route Update Method

In DSDV, the nodes periodically transmit their routing tables to their immediate neighbours. To keep up with the dynamic network topology changes, the node also transmits its routing table if a significant change has occurred in its table from the last update sent, resulting in an update that is both time- and event-driven.

The advertisements received from the neighbours contain the latest route information of the neighbour nodes. Their contents may change dynamically over time. Upon receiving these advertisements, the receiver updates its own routing table for all the entries. This update process is carried out on hop by hop.

Therefore, all the nodes in the network can exchange data with all others and maintain the routes to them even if they are not within range of direct contact.

### 3.2.2 Route Maintenance Method

To maintain the routes for all destinations, the wireless nodes need to make the decision whether to update a route which contains the changes and what to do next. The information for a route includes the destination address, number of hops to reach the destination and the sequence number of this route information. Usually the sequence number is created by the original destination so the newer the number the more recent the route. And when the sequences are the same, the route with a smaller number of hops is chosen.

The routing table updates can be a "full dump" that sends the complete routing table to the neighbours, and could span many packets or an incremental update, which must fit in a packet, including only routing table entries that have had a metric change since the last update. If there is space in the incremental update packet, then entries may be included whose sequence number has changed. When the network is relatively stable, incremental updates are sent to avoid extra traffic, and full dumps are relatively infrequent. In a fast-changing network, incremental packets can become extremely large, and so full dumps will be more frequent.

## 3.3 Cluster Switch Gateway Routing

Cluster switch gateway routing (CSGR) [93] is one of the table-driven routing protocols. Using routing tables, CSGR groups a number of wireless nodes into clusters and controls the cluster with a cluster head. All nodes maintain a routing table with members of the cluster and the head of the cluster. Since the cluster head controls a group of nodes, CSGR develops a form of hierarchy, which is used to manage the whole network.

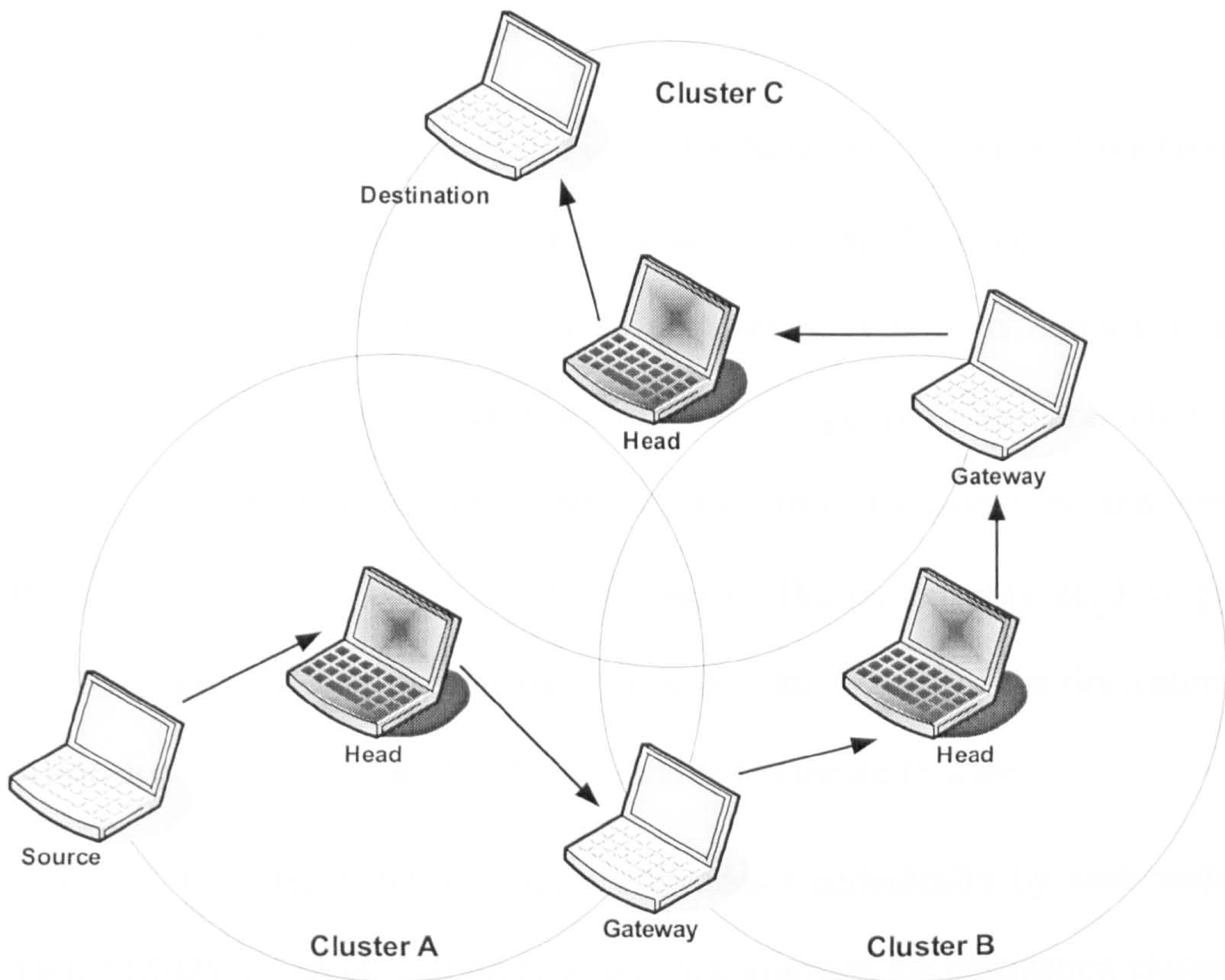



*Figure 3.3 CSGR Routing Discovery Method*

### 3.3.1 Cluster Head

The head of cluster is selected by using a distributed selection algorithm. Although using a cluster head allows some form of control and coordination, it does impose a reliance on other nodes within the cluster. A reselection of a cluster is called for when a cluster head moves away. Since the topology of the network changes frequently, the reselection scheme can cause a problem on spending lots of time converging to a cluster head instead of forwarding data toward their intended destinations. The least cluster change (LCC) algorithm [93] is used to avoid invoking cluster head reselection every time the cluster membership changes. The LCC algorithm requires that the cluster heads only changes when two cluster heads come into contact, or when a node moves out of range of all other cluster heads.

### 3.3.2 CSGR Routing Scheme

CSGR's routing scheme is shown in Figure 3.3. Some modifications have been made to DSDV by defining a hierarchical cluster-head-to-gateway routing approach to route traffic from source to destination. A node is defined as a gateway node when it is within the communication ranges of two or more cluster heads. When a data packet is sent, it first looks for its own cluster head and then searches for the cluster head of the destination. The packet may need to go through cluster by cluster in its search. Once the cluster head of the destination node has been found, the packet is then forwarded to the destination.

In CSGR, the cluster member tables are broadcast periodically by each node using the DSDV protocol. The routing table also contains the destination cluster head for each mobile host in the network. Each node receiving this broadcast message will update its cluster member table. In additional to the cluster member table, each node must also maintain a routing table, which is used to determine the next hop to reach the destination.

Upon receiving a packet, a node will look at its cluster member and routing tables to find the nearest cluster head along the route to destination. The node then checks its routing table to select the next hop to the selected cluster head. So, in order to keep up-to-date information, both routing and cluster member tables in CSGR need to be updated.

# 3.4 Ad hoc On-Demand Distance Vector

The DSDV algorithm discussed above may be improved to give AODV [84], which minimizes the number of broadcasts by creating routes on-demand. AODV, as a reactive routing protocol, only requests the route when it is needed and does not maintain routes that are no longer in use.

## 3.4.1 Route Discovery

As illustrated in Figure 3.4, to find a path to the destination, the source broadcasts a route request (RREQ) packet. The neighbours in turn broadcast the packet to their neighbours until it reaches an intermediate node that has recent route information about the destination, or until it reaches the destination when a route reply (RREP) is sent back to the source. A node discards a route request packet that it has already seen. The route request packet uses sequence numbers to ensure that the routes are loop free, and, to make sure that if the intermediate nodes reply to route requests, they reply with the latest information only.

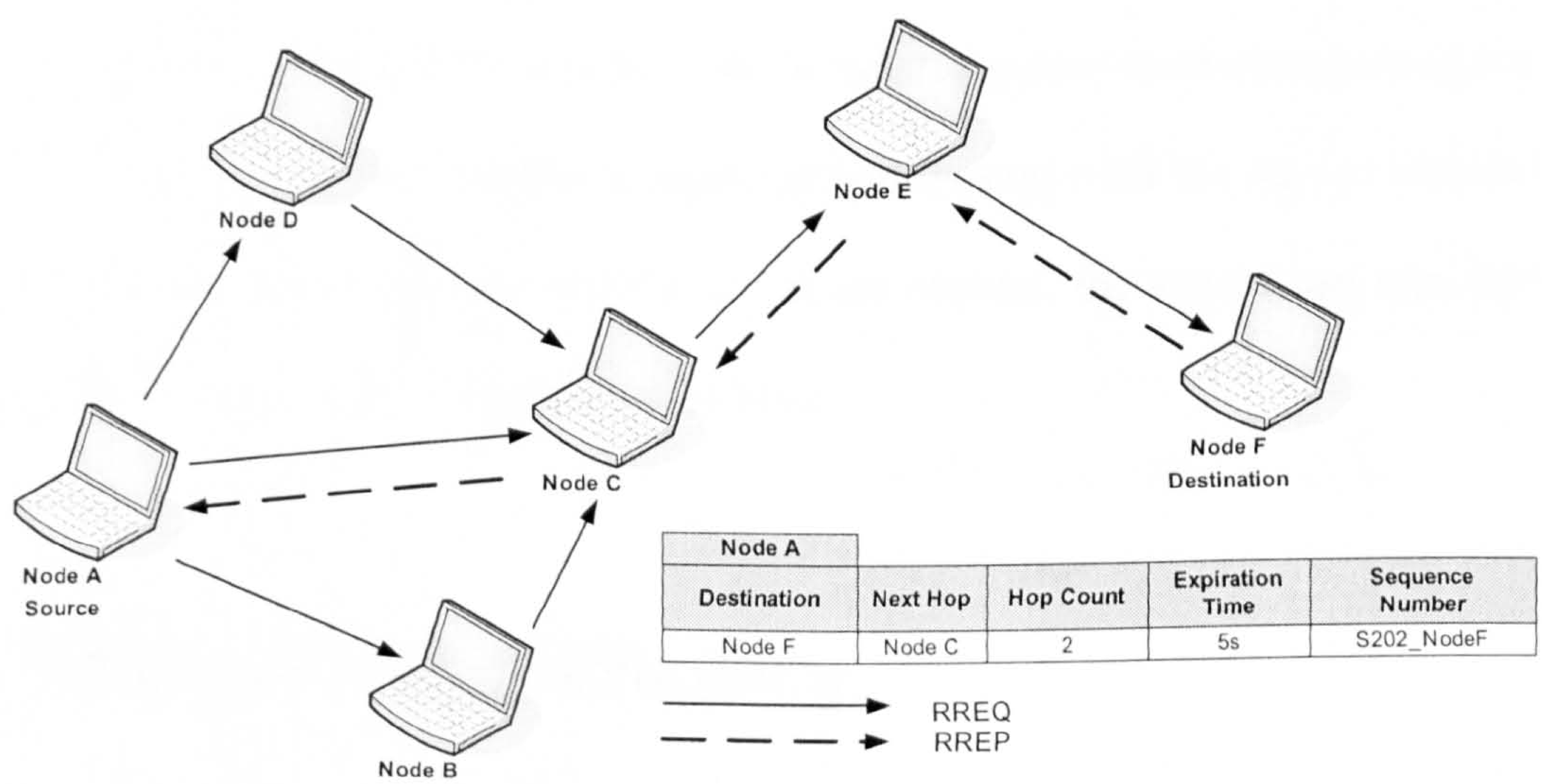



*Figure 3.4 AODV RREQ, RREP and Route Maintenance Table*

When a node forwards a route request packet to its neighbours, it also records in its tables the node from which the first copy of the request came. This information is used to construct the reverse path for the route reply packet. AODV uses only symmetric links, because the route reply packet follows the reverse path to the route request packet. As the route reply packet travels back to the source, the nodes along the path enter the forward route into their tables.

### 3.4.2 Route Maintenance

Using AODV, nodes maintain a routing table with routes to all the destinations that they can currently communicate with. If the source moves, then it can reinitiate route discovery to the destination. If one of the intermediate nodes moves, then the neighbour of the node that has moved becomes aware of the link failure and sends a link failure notification to its upstream neighbours. It will broadcast a route error (RERR) message to its neighbours. Upon receiving the route error message, the neighbours search for the route to the now unreachable destination, which uses the source of the RERR as the next hop. If the route exists, it will be invalidated and the node broadcasts a new route error message to all its neighbours. This process is repeated hop by hop until the source receives the route error message. Depending up on the request, the source can reinitiate the route discovery for that destination again.

## 3.5 Dynamic Source Routing

Source routing is a technique in which the sender of a packet determines the complete sequence of nodes through which to forward the packet. The sender explicitly lists this route in the packet's header, identifying each forwarding hop by the address of the next node to which to transmit the packet on its way to the destination host. It has been used in a number of contexts for routing in wired networks, employing either statically defined or dynamically constructed source routes. Also it has been used with statically configured routes in the Tucson Amateur Packet Radio (TAPR) [99] wireless network. A dynamic method, Dynamic Source Routing (DSR) [100], has been developed for Ad Hoc Networks.

Nodes using DSR maintain a route cache where all the routes to destinations are stored. Entries in the routes cache are continually updated. DSR only initiates the route discovery if the desired route cannot be found in the route cache. Two major phases, route discovery and route maintenance are shown in Figure 3.5.

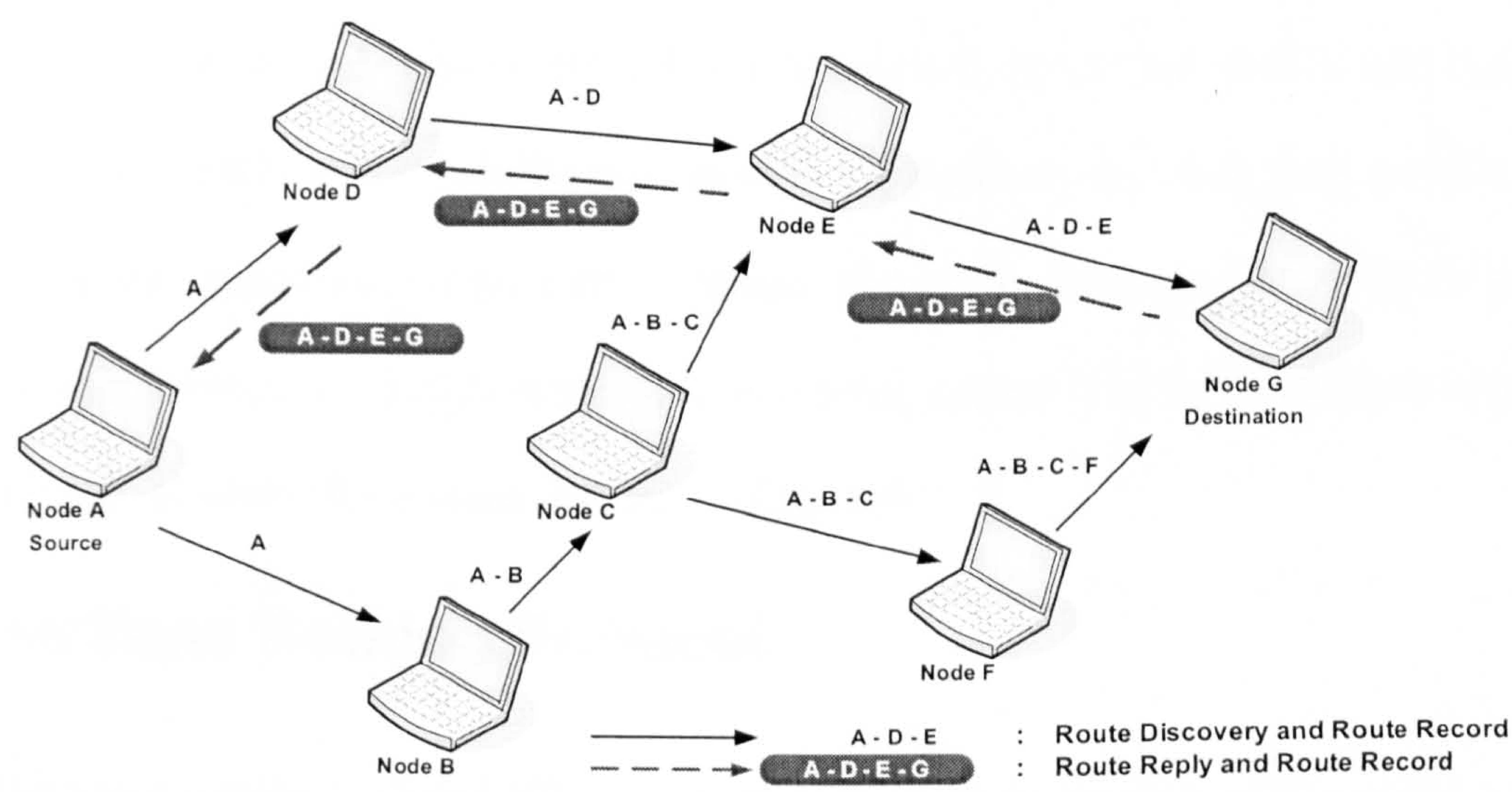



*Figure 3.5 DSR Route Discovery, Route Reply and Route Record*

### 3.5.1 Route Discovery

When the source node requests a packet to send to a destination, it first inspects its route cache to determine if it already has a route to the destination. When a valid route can be found, it uses the route to send its data packet. However, if the node does not have such a route, it initiates route discovery by broadcasting a route request packet. This route discovery message contains the address of source and destination, and a unique identification number. Nodes that receive the packets check if a route to the destination existed in their route caches. If not, they add their own addresses to the route record of the message and forward the message to their neighbours. The propagation stops when the packet reaches either the destination or an intermediate node that contains in its route cache a valid route to the destination. Then a route reply message is unicast back to the source node with the hop sequence from the source to the destination.

### 3.5.2 Route Maintenance

In order to handle route breaks, route maintenance is accomplished through the use of route error messages and acknowledgements. When the node's data link layer encounters a fatal transmission problem, it removes the route from its route cache and generates a route error message. The nodes receiving the route error message remove the hop in error from their route caches. The acknowledgements are used to verify the correct operation of the link.

## 3.6 Zone Routing Protocol

The zone routing protocol [97] is a hybrid protocol incorporating the merits of reactive and proactive routing protocols. A routing zone is determined by a zone radius, which is the minimum number of hops it should take to get to any node. Every node has its routing zone and is a member of other routing zones, which can overlap. ZRP uses a proactive routing protocol within the routing zone of each node. Reactive routing is used to send a packet to a node outside the source's routing zone. The size of a chosen zone can affect MANET communication performance.

ZRP has three sub-protocols: (a) the proactive intrazone routing protocol (IARP), (b) the reactive interzone routing protocol (IERP), and (c) the bordercast resolution protocol (BRP).

### 3.6.1 Intrazone Routing Protocol

IARP uses a proactive neighbour discovery protocol to detect the presence and absence of neighbouring nodes, which is always referred to as a routing zone. Each node maintains its own routing zone to ensure that all nodes within the zone have an up-to-date routing table to all the other nodes in the zone.

### 3.6.2 Interzone Routing Protocol

IERP operates very much like the on-demand routing protocol to search for routing information to nodes residing outside its current zone. It initiates the route discovery process when a route of request to a destination is not locally available. This discovery message will be forwarded by the intermediate nodes until the destination is reached or a route to destination is found in the intermediate node's route cache. A route reply will be sent back to the source to complete the discovery process.

### 3.6.3 Bordercast Resolution Protocol

As the local zone's information is known by IARP, the route discovery for cross-zones becomes simple. The bordercast resolution protocol is used in ZRP. Bordercast means that the route query is directed toward regions of the network that have not yet been covered by the query. If a node is in the routing zone that has received the query, it becomes a covered node. Therefore, the route query is not going to enter other zones but only those between the sources and covered routing zones.

### 3.6.4 Route Maintenance

Since parts of ZRP routing are running different routing protocols, their characteristics will be different. Some parts of the route are dependent on proper routing convergence, while other parts are dependent on how accurate the discovered interzone route is. This can make assurance of routing stability very difficult. Without proper query control, ZRP can actually perform worse than a standard flooding-based protocol.

ZRP's route discovery process is, therefore, route table lookup and/or interzone route query search. When a route is broken due to node mobility, if the source of the mobility is within the zone, it will be treated like a link change event and an event-driven route update used in proactive routing will inform all other nodes in the zone. If the source of mobility is a result of the border node or other zone nodes, then route repair in the form of a route query search is performed, or in the worst case, the source node is informed of route failure.

# Chapter 4 GAW Routing Method



## 4.1 Definition of GAW

### 4.1.1 Overview

In recent years, the issues concerning how a MANET can connect to the Internet have become popular [9, 89]. A MANET does not have central administration and can work with dynamic topologies, which makes it suitable, for example to support infrastructure wireless LANs in emergencies. In such a network, in order to build up communication between wireless nodes on the fly, it is important that the wireless nodes act as both terminals and routers with data delivery and routes discovery abilities. When considering communication to the Internet, the functions of both route discovery to the Internet and routing in the MANET need to be carefully organised.

Some methods of connecting infrastructureless wireless networks and the Internet have been introduced in Chapter 2. They are similar to the traditional wireless LAN Internet connections, which involve base stations and other technologies such as Mobile IP. In these methods, the base stations are used as gateways when the Internet connection is required. Apart from keeping routing information for the MANET, the routing protocols are implemented such as to discover the base stations. However, unlike the case of infrastructured wireless networks, the base stations are not necessarily needed in MANETs since they do not administer the communications for network members. Therefore, it is not necessary to have every node in the wireless domain maintain the base stations' routing information since they are only useful when Internet connection is demanded. Furthermore, Ad Hoc wireless routing protocols are designed to perform the routing task in dynamic networks where no central administration is present. Since a MANET should, when requested, run independently as network, it is better to design a method, which separates the gateway discovery scheme and the routing in the wireless domain.

As discussed in Chapter 2, two approaches can be used to support the Internet connection for MANETs. One method uses a fixed IG (Internet Gateway), which serves as a base station to handle the communication between the two networks. In fact, this definition is developed sharply from the traditional wireless LAN connection and used in some implementations. Another method defines the wireless devices with wired connection servers as the gateway nodes. They are ordinary wireless nodes but with both wired and wireless interface. In MANET to Internet connection, both methods can be used together. It would be good to have an inclusive definition to the service provider, which maintains the independency of having a MANET with or without base stations providing Internet service.

The GAW technology introduced in this chapter is a new routing protocol developed by the author of this thesis at University of Warwick, it proposes a solution for combining Ad Hoc wireless routing and Internet Gateway discovery from both approaches introduced in section 2.5.3. In GAW, the differences between wireless nodes in MANET have been discovered. One group has, and can provide, the Internet connectivity directly and another group which needs to discover the IGs to gain connectivity. From this point of view, the wireless nodes in the MANET are classified in GAW technology as GAW Nodes (GAWNs) and normal nodes. Some exclusive functions are defined in the GAWNs, which ensure the connection ability and maintains the independency of MANET. Furthermore, the idea of GAW routing provides a method for Internet nodes to visit the wireless nodes in MANET.

The following section explains the GAW technology with routing and the Internet connection method. The GAW routing method is designed to make the routing protocol more efficient and to accurately handle the Internet connection task.

## 4.1.2 What is GAW?

The idea of GAW routing method is that it takes into account the features of MANET; in which case each device in MANET is a terminal and a router at the same time. In other words, the device can discover a route and forward another device's routing request. The GAW routing method is developed from the traditional Ad Hoc routing protocol DSDV with some improvements. The most significant difference between DSDV and GAW on Internet connection is that by using the new GAW routing method, one does not have to discover a route to the IG to gain access to the Internet. It can simply find 'someone' in the routing table who can offer such connectivity. One of the new features of GAW is its new route update and route selection method. As a result, in the GAW routing method, the route discovery process is quicker and more efficient that in similar protocols.

The name of "GAW" (Gateway Awareness) comes from the definition for the GAWNs, where the gateway refers to the IG located on the wired network. GAWNs are mobile nodes selected from the wireless domain. Described in Figure 4.1, they are defined as 'gateway aware' because they know the IGs, by direct contact, or they are gateway nodes with both wired and wireless interface, rather than informed by others. As a result, they have direct contact to the Internet and do not need to be routed by other wireless nodes.

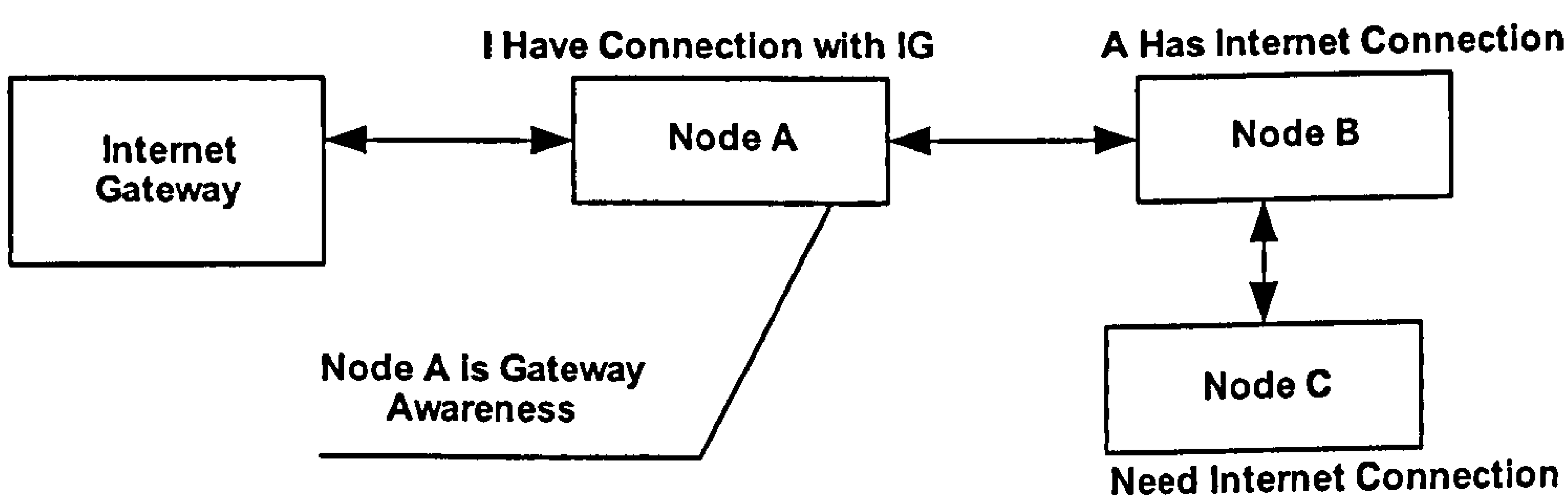



*Figure 4.1 What is Gateway Awareness?*

There are two types of GAWNs corresponding to the two connection methods. In the first method, wireless nodes are defined as GAWNs by being nodes within the direct propagation range of the IG. These GAWNs discover the existence of IGs directly by receiving information broadcast from them, at which point they form the interface between the Internet and the MANET. In this case, when GAWNs move out of the ranges of IGs and no longer have direct awareness of IGs, they transform themselves into normal wireless nodes by terminate the functions of GAWNs. In the second method, if a wireless node gains an Internet connection by having a wired interface, for example an Ethernet port, it is defined as a GAWN too. In this case the wireless node itself works as the gateway node between two networks. When these GAWNs lose wired connectivity, they no longer serve as gateway nodes.

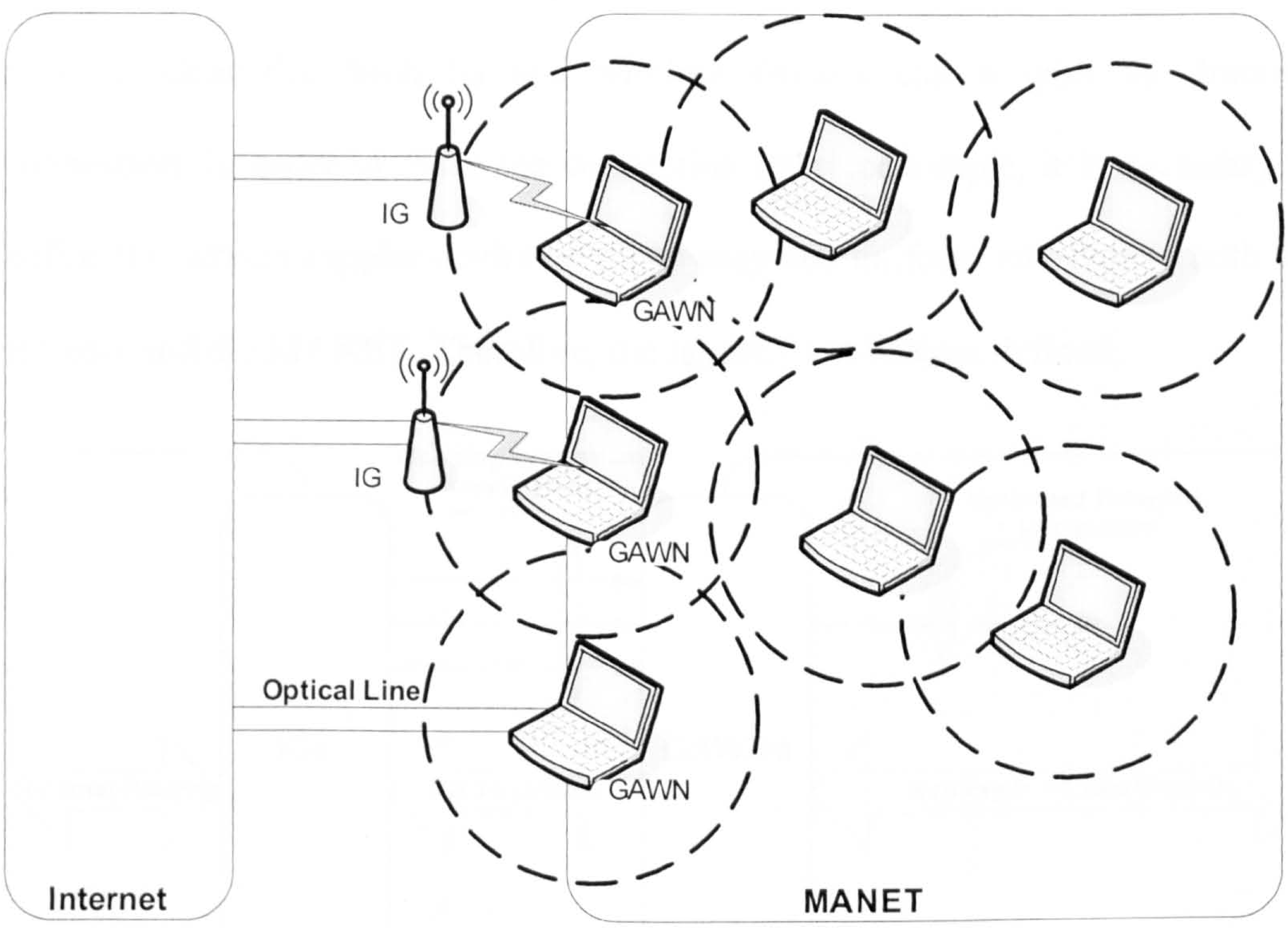



*Figure 4.2 Definitions of GAWNs*

As shown in Figure 4.2, the definition of GAWNs creates a layer of wireless nodes in MANET with different characteristics, who set up an interface between the two networks. The advantages of having this layer are discussed in 4.1.3. The GAW routing method uses these advantages to maintain the information for these nodes for the Internet connection purpose so that the Internet connection tasks become easier and more accurate.

### 4.1.3 Why Define GAWNs?

In infrastructure wireless networks, base stations are the administrators, supporting the communications for all the network members. As a consequence, they become the IGs when Internet services are requested. However, a MANET does not need any central administration. The IGs are employed only when a request to the Internet is made by a wireless node. The definitions of GAWNs make it clear that both IG and wireless devices can support the Internet connection. In order to make the connection interface simple, it is necessary to define the service suppler devices with an easy and uniform interface to both the Internet and the MANET. Therefore, the layer of GAWNs is defined.

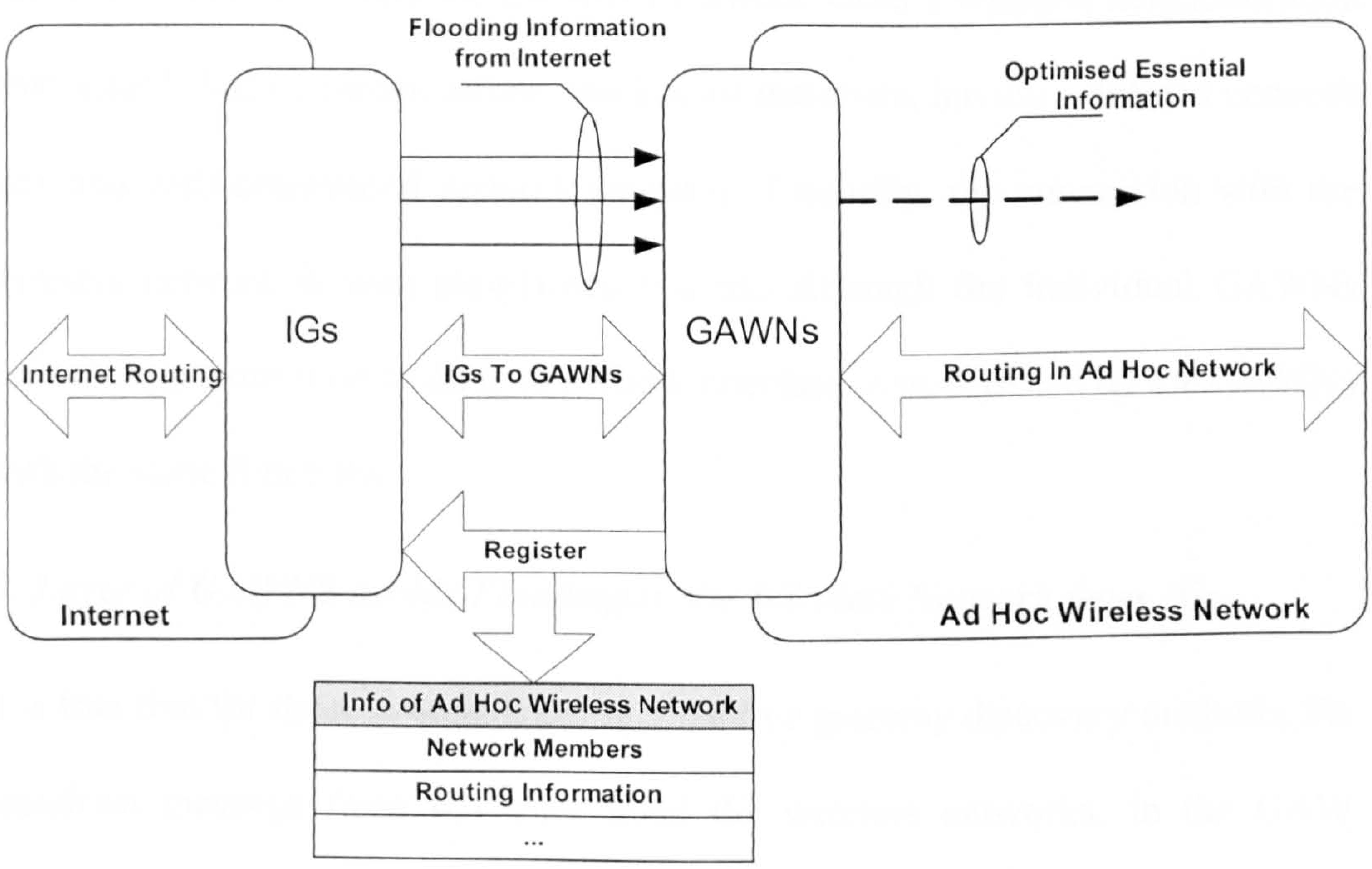



*Figure 4.3 What GAWNs can do?*

Given the fact that all the requests to the Internet from wireless nodes will definitely use one of these GAWNs as the final host on the selected route by the routing protocol, they have some special features compared with other wireless nodes. GAWNs are defined with special functions to support the MANET routing and Internet gateway discovery method. These functions are called whenever a wireless node gains the Internet connection from IGs or itself. They will be dismissed as soon as a node no longer serves as a GAWN. The main functions associated with the features of GAWNs are summarised in Figure 4.3.

*A. Using GAWNs to setup of the Interface for the Internet.*

Consider the dynamic MANET topology, the layer of GAWNs has to provide a stable interface between the MANET and the Internet. The GAWNs' interface minimises the complexity and uncertainty of the highly dynamic wireless networks. With the GAWNs, the wired network faces a wireless neighbourhood with established communications and known members, having a defined network size and well-determined network structure. Crucially, the connection with the wireless network is well maintained because although the individual GAWNs may change from time to time, the whole interface is maintained by the GAWNs with the same functions.

*B. Layer of GAWNS avoids Flooding in the Wireless Network from IGs.*

It is true that for those protocols using proactive gateway discovery methods, the broadcast message from IGs may flood the wireless networks. In the GAW routing method, the proactive gateway discovery method is used. However, the periodic advertisement from any IGs stops at the GAWNs. The Internet connection discovery for other wireless nodes will be carried out by the GAW routing method. Therefore, the flooding effect is stopped without affecting the connection service. Changes in the situation of a GAWN, as a result of information from an IG, occur fast and thus the likelihood of data being dropped due to an incorrect GAWN identity is minimised.

*C. GAWNs discovery of the route to the IG.*

As the name implies, GAWNs are the first layer of wireless nodes that have direct contact with the Internet. The primary function of facing the Internet is to discover the connection, for example through IGs. The GAW routing method uses a proactive gateway discovery method. In another words, GAWNs will wait for the IGs' broadcast messages. By receiving the advertisements from the IGs, the GAWNs discover and maintain the information for routes to the Internet. They are the only nodes that have direct contact with the Internet, so they have the most up to date information. All communications from the mobile network to the Internet depend on GAWNs, via which other mobile nodes can find route to reach the Internet using Ad Hoc routing protocols.

*D. GAWNs simplify the Internet Connection Task.*

Having GAWNs simplifies the connection task for wireless nodes. Because they do not need to discover an IG but rather contact the GAWNs, to whom the Internet connection task has been delegated. As a result, the connection services are not offered by certain IGs but by a layer of well-maintained interface. This transforms the Internet connection task into 2 steps, a normal data communication within the MANET from sources to the layer of GAWNs and the data transformation between GAWNs and the Internet. The GAW route selection method helps the nodes to choose the GAWN that is most likely to have a current

Internet connection. The definition of GAWNs also eliminates the concerns for different IGs. The connection availability is determined by the number of GAWNs, which implies the number of available routes to Internet.

*E. Load balancing between GAWNs.*

The route selection scheme of GAW has a more flexible algorithm to discover the route when multiple GAWNs exist to perform the essential load balancing. It is obvious that data packets from both networks go through the GAWNs. Since there may be more than one GAWN, the packets, including data packets, route update packets, route discovery packets and the address configuration packets, need to choose the best route according to the routing algorithms. GAWNs' energy will be excessively consumed if one GAWN is chosen all the time. The routing algorithm optimises the resource of the GAWNs with the essential load-balancing scheme.

*F. Data Exchange between MANET and Internet is improved.*

The GAWNs can be seen as the representatives of the MANET and allow the wired network to probe the unknown structure of the wireless domain. Data exchange between the IG and GAWNs manages to build up a database for the wireless network on the IG, from which the locations of wireless nodes are easily determined. This function enables the wireless network members to register with IGs through the GAWNs. After the exchange, the Internet can determine the size of the attached wireless network, the members of this network and if there are any other GAWNs from the same MANET. The IGs update their routing table and share the information through wired routing protocols. Therefore, the database also helps the wireless nodes search for other wireless nodes in the different domains through out the Internet if all the nodes have connection to the Internet.

# 4.2 GAW Routing Method

## 4.2.1 GAW Routing Overview

The GAW routing method is designed based on the definitions of GAWNs and combines both MANET routing and the Internet gateway discovery method. Figure 4.4 shows that the idea of GAW simplifies the Internet connection into a two step process, a normal Ad Hoc routing from wireless nodes to GAWNs, followed by the direct connection between GAWNs and Internet (i.e. IGs). These two steps are performed by using the GAW routing method inside the MANET and a proactive gateway discovery method respectively. The desired functions of GAWNs are defined in order to support the routing performance.

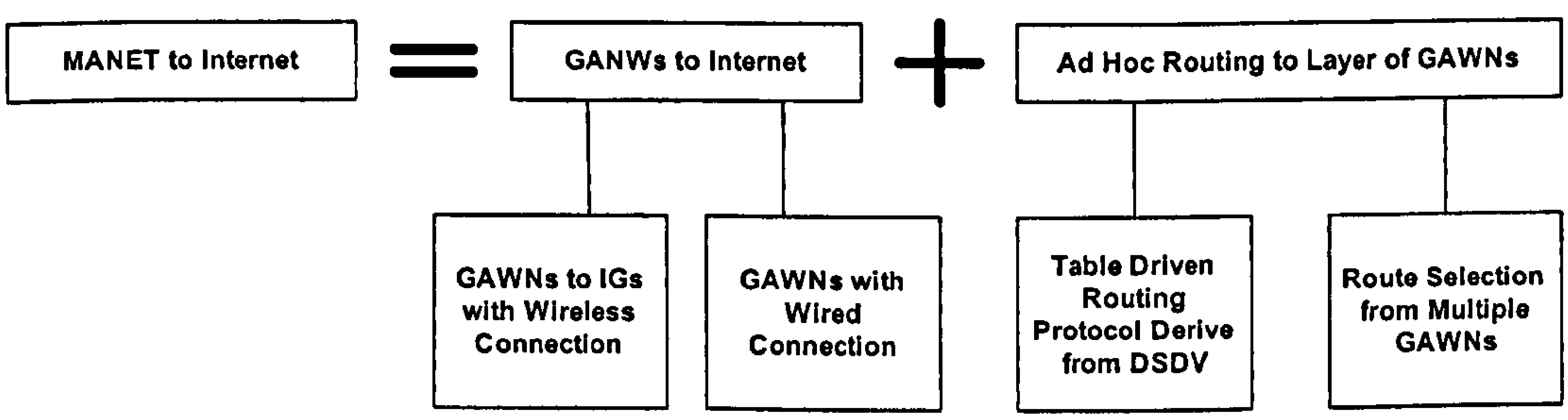



*Figure 4.4 Two Steps Internet Connection process with GAW Routing Method*

Given the routing algorithm originally developed from DSDV, the GAW routing method uses the routing table to maintain the destinations' information for the MANET. The table contains, along with the destination addresses, routes and numbers of hops to the destinations, and the metrics calculated from the number of hops between source and destination. Furthermore, the GAWNs are clearly marked, so that they can be easily located when a route request to GAWNs is demanded. In addition, a parameter of the GAW state is held for all GAWNs as well. The state is given to each GAWN to clarify the availability of the current route to Internet. With the GAW mark and GAW state, a layer of GAWNs is formed and stored in the routing table. The information for GAWNs will be updated together with the other routing information, with minimum effect to the Ad Hoc routing process. Thus the mobile nodes can discover which GAWN in their routing table is currently the best choice.

The GAW routing method has a proactive route update process. All the information used in the GAW routing method is gathered in a passive form by receiving update messages from neighbour nodes. The routing table can be updated according to the messages received either periodically or triggered when necessary. The nodes will not initiate detection of broken links but rather use a default timer to each destination in their routing tables. The link to one destination is assumed to be lost if no update message for the destination is received after the default timer has expired. The information update for IGs is also proactive. GAWNs receive IGs broadcasts to maintain awareness of the connectivity to the Internet. A timer is also used to dismiss a GAWN if it expires.

The GAW route selection method supports the routing information for all communication inside the MANET. Generally speaking, the route selection is initiated by searching for the destination address in the routing table for the route. If the route to the destination is not present in the routing table or on the Internet, the packets will be forwarded to the Internet through a selected GAWN to perform further route discovery. The communication between the wired and the wireless network all go through the GAWN layer. The GAW route selection scheme optimises the route between sources and GAWNs and provides the essential load-balancing scheme between GAWNs.

Features in the GAW routing method will be explained in the following sections including routing table parameters, route update method, route selection scheme, GAW state and broken link process.

### 4.2.2 Routing Table Parameters

The GAW routing table contains the essential information to support the routing function. The GAW routing method is developed from DSDV using the distance vector as the routing metric and a sequence number for each route. It incorporates two other new parameters, GAW mark and GAW state. An example of a GAW routing table is shown in Table 4.1.

*Table 4.1 GAWNs and other Destinations in the Routing Table*

| Destination | GAW/IG Mark | Metric | Sequence Number | GAW State | Next Hop | Expiry Timer |
|---|---|---|---|---|---|---|
| Node B | Null | 1 | S180_NodeB | Null | Node B | 15 |
| Node C | Null | 1 | S206_NodeC | Null | Node C | 10 |
| ... | ... | ... | ... | ... | ... | ... |
| Node D | Null | 1 | S060_NodeD | Null | Node D | 10 |
| Node E | GAWN | 2 | S288_NodeE | Identified | Node C | 15 |
| Node F | GAWN | 3 | S120_NodeF | Uncertain | Node C | 8 |
| Node G | GAWN | 3 | S300_NodeG | Identified | Node C | 15 |
| ... | ... | ... | ... | ... | ... | ... |

When GAW is developed, the original parameters in DSDV are not enough. There are two reasons for the new parameters. The first one is that all destinations in DSDV appear to be the same in the destination list. Whilst, in GAW routing method, GAWNs are different from others with unique functions since they are the devices with Internet connections. A parameter is needed to identify the GAWNs in the routing table. Secondly, a scheme needs to be developed to update the Internet connectivity information for GAWNs. Since such information is different from the normal MANET routing information, another parameter shows the connectivity is needed.

The GAW mark and GAW state are then added into the GAW routing table. These two parameters work with other routing table parameters to support the new routing method for GAW. The parameters in GAW routing table are explained in the following parts. The GAW state will be fully discussed in section 4.2.5.

- ***Destination ID/ address.*** This parameter is the identity of the destinations in the routing table of a wireless node. It can be an IP address, an unique ID or other formats. Along with the other parameters in the routing table, it helps the source discover whether the destination is reachable or not. It also ensures that every host forwarding the message can guarantee the same node as their destination.

- ***GAW/IG mark.*** This parameter is to identify the available GAWNs among the destinations, and will be called when the destination address is out of the routing table. In the routing table, the addresses of the GAWNs are among the destination list. With the mark, the address of those service nodes will be easily located when an Internet connection is required. The destinations with a GAW mark form a layer of GAWNs where the load-balancing scheme can be applied in the route selection. For GAWNs, the destination with IG mark signifies Internet Gateways. The information for IG is updated when a new advertisement from IG is received and will not be broadcast to the rest of the wireless network.

- ***GAW state.*** Another parameter added into the routing table associated with the GAW routing method is the GAW state. Network topology changes in MANET mean that the movement of a GAWN out of the range of an IG is a frequent occurrence. Therefore, the currently employed GAWN may not be available for Internet connection for the next packet. Working together with the GAW/IG mark, the GAW state helps the mobile nodes to be updated with the changes as soon as possible, providing more reliable transmission channels for Internet connections. As defined in the GAW route update method, the GAW state changes are always forwarded to the whole network immediately, resulting in a good response to the crucial GAWN changes.

- ***Sequence number and route metric.*** They are the original parameters from DSDV. A sequence number is generated each time the routing table is sent by the destination node. These numbers can help the mobile nodes find out if this routing update is an old one or a new one. They are also used as a reference in the route selection process. The route metric shows the distance in hops between the source and the destination. The shorter the metric, the shorter the distance is. Based on these metrics, the shortest path first algorithm [66] is used for the routing table update and route selection.

- ***Next Hop.*** Next hop is the node which is the next one on the route to the destination. The route update process decides which nodes are used on the routes to destinations. It is obvious that the next hop is also one of the destinations in the routing table. Therefore, when the route selection scheme has found the desired route to the destination, it forwards the packets to the next hop that has the ability to proceed with the delivery.

- *Expiry Timer.* The expiry timer sets the available time for each entry in the routing table. The timer is updated when new route information is received for a destination. Different timers are used according to the destination's type. The expiry timer for IG, GAWN and normal wireless node will be introduced in the following sections. After the timer for a route expires, the route is no longer available to be used.

The routing table of GAWNs maintain extra routing information for the IGs. The IG address is stored in the destination address list. Each time a broadcast from an IG is received by the GAWN, this IG will be updated so that the connection remains available. In the GAW mark place, an IG mark is given to clarify it so that it can be found when needed. However, the IG's information will not be broadcast to the network so as to avoid flooding.

### 4.2.3 Route Update Messages

In the original DSDV, the route update process uses two types of update messages; periodical update message and trigger update message. These update messages carry the routing information maintained by the current nodes. To achieve the best update to the network topology, the content and broadcast frequency of these update messages need to be chosen carefully. For example, too many update messages may flood the network with redundant data packets. Insufficient update messages may leave the nodes with out-of-date routing tables resulting in the wrong delivery of data packets.

In the context of the Internet connectivity, the periodical and trigger update messages can be used as an option. However, unlike routing in MANET, the route update for IG is also dependant on IG's broadcast interval, which is irrelevant to the MANET route update. Experiments (which will be discussed in Chapter 5) show that simply using periodical and trigger update messages may cause slow response to connectivity changes and cannot stop flooding the MANET. In the GAW routing method, to support the Internet connection, two new update messages, GAW identification and GAW cancellation messages are created. They are sent out by GAWNs and work with the proactive IG discovery method to provide a quick response to any changes regarding the Internet connectivity. In the GAW state change process (which will be introduced in section 4.2.5), the GAW identification message is used to identify a node as GAWN and the GAW cancellation message is used to end the function of GAWNs. Table 4.2 shows the sender, frequency and content of all the update messages used in GAW routing method. The routing parameters that are sent out by the GAW update messages are shown in Table 4.3.

*Table 4.2 4 Different Update Messages in GAW Routing Method*

| Update Messages | Sender | Frequency | Content |
|---|---|---|---|
| Periodical Update Message | All Nodes | Periodical | All Routing Table Entries |
| Trigger Update Message | All Nodes | Event Driven | Entry That Changes |
| GAW Identification Message | GAWNs | Once Only | Entry That Changes |
| GAW Cancellation Message | GAWNs | Once Only | Entry That Changes |

*Table 4.3 Parameters that are Sent Out by Update Messages*

| | | | | |
|---|---|---|---|---|
| Destination | Metric | GAW Mark | GAW State | Sequence Number |

Periodical update messages and trigger update messages are different in their contents and their broadcast frequencies. Both of them are used for all the wireless node update processes including GAWNs. Additionally, to those nodes who are known as the GAWNs, two broadcast messages are designed to update their essential information, the GAW identification message and the GAW cancellation message. The following section will introduce these update messages.

*A. Periodical Update Messages*

In the GAW routing method, periodical update messages are generated by wireless nodes every default update period and broadcast throughout the whole MANET. However, unless responded to by others, the wireless node does not know if this information is correct or has been changed after the last periodic update. All the information held in the routing table is assumed to be correct and is thus broadcasted. A node also broadcasts itself as the message's source to its neighbours so that others will know it is still within reach.

The broadcast period is fixed, which can be set according to the wireless node's mobility. A longer broadcast period is used when the wireless nodes' mobility is low. However, if the wireless nodes' mobility is high, the broadcast interval should be set shorter so that the network changes can be delivered to all the network members without long delays.

Upon receiving the periodical update messages, wireless nodes make updates accordingly so that route information synchronisation between the neighbouring nodes is maintained. The periodical update messages from neighbours keep the wireless nodes aware of the topology changes around them.

The GAW routing method uses periodical update messages in the MANET as the essential 'updater messages' for all wireless nodes, including GAWNs. For normal wireless nodes, all information in the routing table is sent out including those for themselves. For the GAWNs, an extra step is taken. GAWNs look at the IGs information they currently keep and generate GAW states accordingly before sending them out. Therefore, when GAWNs send out their periodical update message, GAW states are refreshed and attached. The GAW state will be introduced in 4.2.5.

***B. Trigger Update Message***

*Table 4.4 Evens that cause Trigger Update Messages*

| Events | Descriptions |
| --- | --- |
| Broken Link | Timer to a destination expired and no update message has been heard . |
| Old Route information from Neighbour Nodes | Neighbour send in a route information with older sequence number |
| GAW State Changes | GAW Identification and Cancellation Messages and other GAW state change messages |

In the GAW routing method, the trigger update messages are defined to be an assistant to the periodical update messages. After the periodical update messages are sent out, some information in the routing table may have changed before the next periodic update message is due. In the GAW routing method, a trigger update message is generated when the routing table content changes significantly between periodic updates and only the changed information is sent. As shown in Table 4.4, the significant route changes include a broken link, which is for any destination, incorrect route update information from neighbours and GAW state changes. The first two events are in the original design of DSDV. The GAW state changes event is newly added to support the GAW routing method. When the neighbours receive the trigger update messages, they will decide if it is necessary to forward them further. For example, when a node detects a broken link for one destination, it uses a trigger update message to inform its neighbours so that they know about these changes before the next periodical update is due. All the neighbours that get this message may update accordingly.

The trigger update message makes update additional to the periodical update message and can eliminate the time delay for some crucial route changes without the use of a periodical update message, which may contain redundant data. However, too many trigger update messages are also a problem, so if quite a lot of the routing table parameters change, instead of a trigger update message, a periodical update message will be called. As a result, the next periodical update is now moved forward. The GAW routing method applies the same roles on this that, if more than 3 routes have changed since the last periodical update message is sent, a new periodical update will be called.

GAW state changes may affect the route selection decision when a request to the Internet is made. In order to offer the best Internet connectivity ability in the GAW routing method, a trigger update message is sent out whenever the GAW states are changed. All the wireless nodes that receive GAW state change messages have to immediately forward them to their neighbours, if the states they hold are different from those that they receive.

*C. GAW Identification message*

The GAW identification message is a broadcast message only sent out by the GAWNs when they transfer themselves from normal wireless nodes to GAWNs. When the wireless nodes receive the broadcast message from the IG for the first time, they become GAWNs and run the defined GAWN functions. An identification message is generated to inform all the other network members that a connection to the Internet is available through this GAWN.

This broadcast message contains single route information for the original GAWN only. After the GAWN sends out this message, it will initiate a periodical or trigger update message regarding any state changes. A timer is setup on the GAWN as the lifetime for an IG.

*D. GAW Cancellation message*

The GAW cancellation message is sent out by the GAWN when it believes that the Internet connection is completely lost. The message is used by the GAWNs with both wired and wireless interface to cancel their duties, when the GAWNs are sure to have lost the Internet connectivity. GAWNs with wireless connections to IGs use this message to change their states first and then cancel them in due course. This message is broadcast to the network so that all nodes receiving the cancellation can immediately delete the referred GAWN from the available GAWN list. It is different from the trigger update message for a broken link because the original GAWN may still be approachable in the routing table as one of the destinations, which may not be true for a broken link. Both GAW Identification and Cancellation message, are forwarded immediately by the receivers with trigger update messages.

### 4.2.4 Route Update Process

In the GAW routing method, the route update process of a wireless node is a passive form by receiving the update messages from its neighbours; this is the same as in the case of DSDV. Upon receiving these messages, wireless nodes compare every entry with their currently held routing table. The results are used to decide how to make an update and what to do next. Developed from DSDV, the GAW routing method uses a similar route update process. The only difference is that when the destinations are GAWNs, the update process involves the new parameters in the routing table. Since only GAWNs are updated differently, this arrangement minimises the effect on the independency of MANET caused by the broadcast messages from IG. This section introduces the route update process in the GAW routing method.

### *A. Update Process for Normal Wireless Nodes*

The GAW route update method for normal wireless node is developed from DSDV. When a route update message is received by wireless node *A*, the routing information to all the destinations in the message is read one by one. For each of them, node *A* looks for its destination address from *A*'s routing table. If the destination is not in the routing table, this new destination with its routing information will be updated for node *A*. When a match address is found, node *A* compares the new routing information with its own one for every detail.

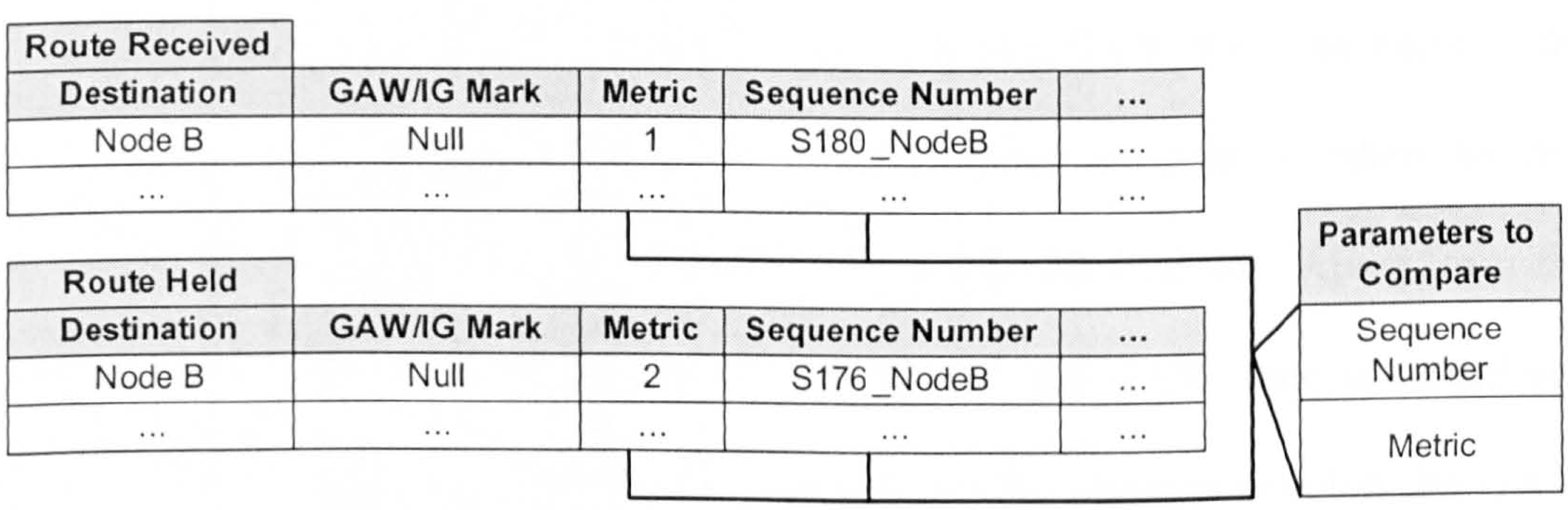



*Figure 4.5 Route Update for Normal Wireless Node*

The update process is shown in Figure 4.5. The first parameter examined in the route update method is the sequence number. Since the destination node generates the sequence number, the newer the sequence number is, the later the routing information is. Therefore, nodes always retain the route with the newest sequence number. When the sequence numbers are the same, the route with the shorter route metric, in terms of hops to that destination, is selected.

After these updates, node *A* has the latest route information of its neighbours and updates itself accordingly. Based on the update results, node *A* decides whether a route update message needs to be forwarded. For example, when the neighbour nodes may have some out of date routing information, node *A* generates a trigger update message with the correct routing data to inform them. To node *A* itself, if the update result shows significant routing table changes (3 changes which is the same scheme as DSDV), node *A* will call a periodical update message and broadcast to all its neighbours. The same update process is repeated hop by hop between all the network members. Therefore, any possible route inaccuracies will be updated through this process.

***B. Update Process for GAWNs***

Shown in Figure 4.6, the route update method for GAWNs is similar to that for other wireless nodes. In the normal periodical update message and trigger update message, it is easy to determine if a destination is a GAWN on the basis of the GAW mark. To these messages, the usual update process is taken so that GAWNs information is updated as for one of the destinations. Apart from the destination sequence number and the route metric, the GAW state is considered as well when making an update decision. When the changes involve the GAW state, the changes are broadcast as trigger update messages immediately. This action ensures that the channels to the GAWNs are well maintained.

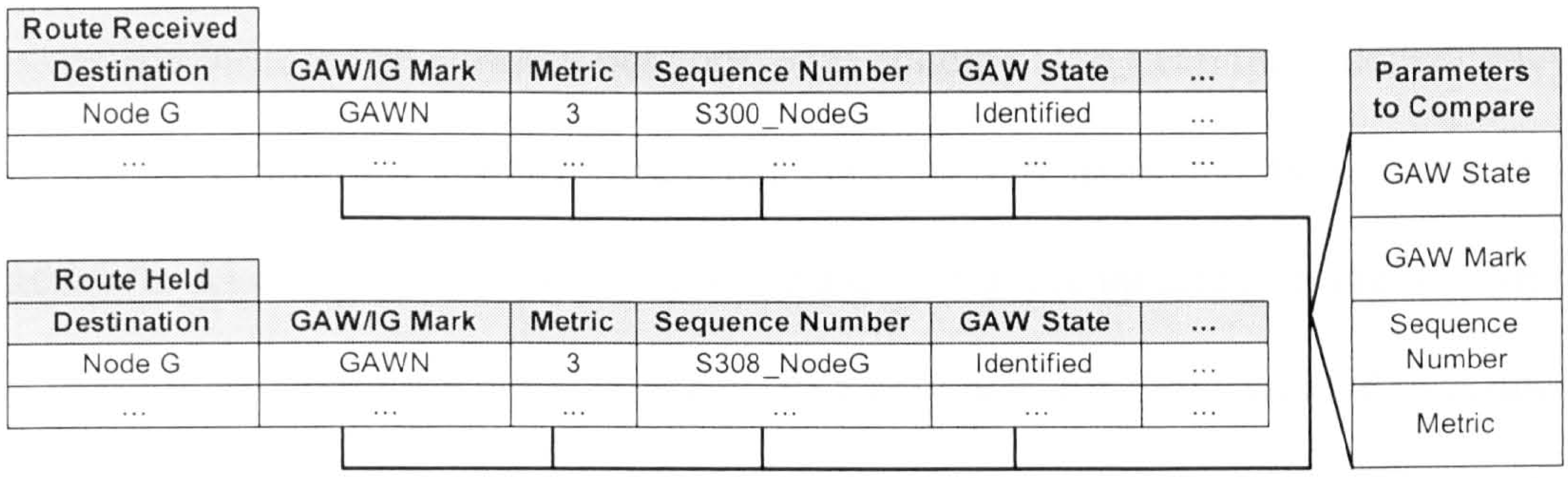



*Figure 4.6 Route Update for GAWNs*

When a wireless node receives GAW identification messages, it may be the first time it becomes known that the destination serves as GAWN. If so, the GAW mark is given to this destination, provided the destination is already in the routing table, following an immediate forward of this message. Similarly, when a GAW cancellation message is received, the corresponding GAW mark is changed back to that for a normal wireless node following an immediate forward of the message.

### *C. Update Process for IGs*

An update between GAWNs and IGs is shown in Figure 4.7. The IGs' broadcast message is periodically sent to GAWNs. Upon receiving it, GAWNs list IGs as the entries in the routing table and conduct the update process. When the GAWNs broadcast their routing table to IGs, they use the normal periodical update messages and trigger update messages as if to another wireless node. The messages contain all the routing information in the GAWNs for the MANET. The IGs then update their own routing tables accordingly.

In some cases, IGs can have more routing information for the wireless nodes since they use a wired routing protocol to keep data synchronised from different GAWNs. As defined in the GAW routing method, the IG's routing tables are not broadcast to the wireless networks. In the MANET, all requests to unknown destinations will be directed to the IGs and may possibly find the route through other IGs back to the wireless network. This scheme is to keep the independency of Ad Hoc wireless routing since the route is not available in the wireless network. As a result, in the GAW routing method, route updating in the MANET is independent from the wired network. It is very possible that a route that cannot be found in the Ad Hoc routing table may be available through the Internet. The information sharing between IGs is out of the scope of this thesis.

Route Received

| Destination | GAW/IG Mark | Metric | Sequence Number | ... |
|---|---|---|---|---|
| Node M | IG | 1 | S282_NodeM | ... |
| ... | ... | ... | ... | ... |

Route Held

| Destination | GAW/IG Mark | Metric | Sequence Number | ... |
|---|---|---|---|---|
| Node M | IG | 2 | S284_NodeM | ... |
| ... | ... | ... | ... | ... |

| Parameters to Compare |
|---|
| Sequence Number |

*Figure 4.7 Route Update for IG*

***D. Expiry Timer Setup***

The expiry timer, as one of the parameters in the routing table, is not broadcast and will be set by a receiving node after conducting the update process for any entries. In the GAW routing method, for any wireless destinations including GAWNs, the timer is set equal to the periodical update interval, which is the maximum delay time for one available route to be updated. Each time a route update is made, the timer for that route is reset. When the timer expires and no more route information is received, a trigger update message for a broken link will be generated. GAWNs also set an expiry timer for the connected IGs. A GAW cancellation message will be made once the timer expires.

### 4.2.5 GAW State

To assist in the fulfilment of the functions of GAWNs, each one has been assigned a defined state which is attached to its address in the routing table. The defined GAW states are identified GAWN, uncertain GAWN and cancelled GAWN (which is equal to a normal wireless node). For the service period of a GAWN, its identified and cancelled states are the service starting and ending points. With the definitions from the GAW state, the route selection process of the GAW routing method becomes more efficient and accurate. The state change of a GAWN is decided by the expiry timer it has to the IG and the node's movement in the wireless network. Figure 4.8 shows the GAW state change with update message to form the circle of nodes. This section explains the properties of each state and the relation between them.

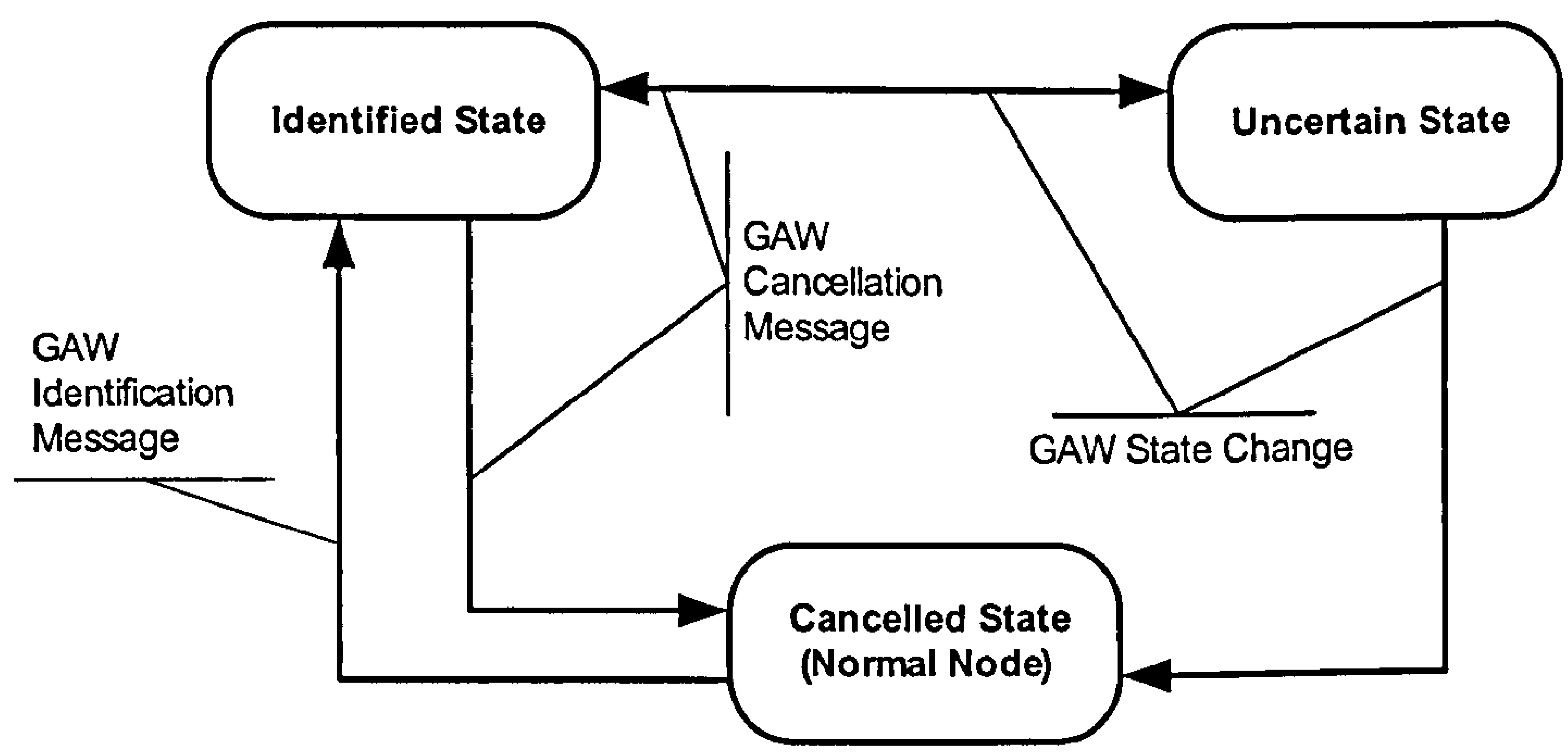



*Figure 4.8 GAW State Changing Circle*

### *A. Identified State*

Identified state is the starting state of a GAWN. As one of the parameters in the routing table, the identified state is associated with GAWNs and generated by GAWNs when they receive the broadcast from IGs. If the broadcast message is constantly received before the timer has expired, the identified state is generated by the GAWN and sent out with normal routing information. Therefore, a GAWN with an identified state in the routing table shows that the GAWN is currently maintaining a direct connection to the Internet. The GAW route update process is designed to make a quick response to the GAW state changes. So, all the GAWNs with identified states in the routing table are assured to have the most up-to-date delivery service to the Internet. When wireless nodes select a route to the Internet, the routes to GAWNs with identified states always have the highest priority. In the node's routing table, the identified state is given to the GAWN with an Identified mark.

***B. Uncertain State***

The uncertain state is a temporary state of a GAWN. As one of the GAW states, it is associated with GAWNs and generated by GAWNs. The uncertain state means that the connectivity service through this GAWN is not guaranteed. It may turn to any of the other two states depending on the situation onwards. The uncertain state is generated by the GAWN when no broadcast message from Internet Gateway is heard after the timer expires. In fact, depending on the IG expiry timer setup methods, an uncertain GAWN does not mean the route to Internet through this node is completely unavailable. There are two ways to setup an expiry timer for the IG. One is simply using the periodic update message period in the wireless networks as the expiry time for the IG. However, this setting may result in timer asynchronies with the IG broadcast periods. For example, if the IG broadcast period is longer than the expiry timer, a GAWN's state can be set as uncertain whilst it still has the Internet connection. Another way is to set this timer to be the same as the IG broadcast period. In this case, an uncertain GAWN has certainly lost the connectivity to the IG. GAWNs with uncertain state are only selected when no identified GAWNs are present. In the routing table, the uncertain state of one GAWN is indicated with an Uncertain mark.

### *C. Cancelled State*

Cancelled state is the ending state of a GAWN. It is normally set by a GAWN after it has been in the uncertain state for a period of time (equal to the periodical update interval) or when a GAW cancellation message is received. The change into the cancellation state means the GAWN needs to change its functions back to that of a normal wireless device. The wireless nodes receiving this message first delete the GAW mark for the GAWN and then forward the message to all their neighbours. A cancelled GAWN is no longer different from other destinations in the routing table of a wireless node. Note that the cancelled state for a GAWN only means the connection to Internet is not available through this node. However, as one of the destinations, it can still be approachable by the rest of the network members.

### *D. GAW State Update*

All these GAWN states are generated by GAWNs and sent out to the rest of the network using the route update messages. The GAWN state is refreshed and attached each time a periodical update message is sent out. When a GAW change is made, the trigger update message is used to inform all other members in the wireless network. Additionally, as discussed in 4.2.3, there are two update messages specially designed to help the GAWN state changes, the identification massage and the cancellation message. Upon receiving these update messages, all the wireless nodes update the GAWN states together with the general route information for GAWNs. Therefore, in the routing table of each wireless device, all GAWNs are listed with their current states.

### 4.2.6 Route Selection Scheme

One special feature of wireless nodes in a MANET is that, apart from sending and receiving data packets, they also forward packets from other nodes to different destinations. In other words, they are both terminals and routers. Developed from DSDV, the GAW route selection method introduced here combines the route selection inside the wireless domain and route discovery to the Internet. When Internet connection is demanded, the GAW route selection method turns the single route selection process to IG into the multi destination selection process to GAWNs. It works closely with GAW load balancing to provide the optimised routing performance.

To start the route selection, a wireless node first searches for the entries from its routing table. From the previous route update process, each wireless node maintains a routing table with routes to all the approachable destinations. The search result classifies the demanded address into 2 groups, an address in the routing table and an unknown address. The latter includes both addresses on the Internet and addresses outside the routing table. Due to the asynchronies of the route update process, a destination address can be in a different group on different nodes. The following sections will introduce the route selection schemes for these two groups respectively.

*A. Route Selection to Approachable Wireless Destinations*

To the destination address in the routing table, the route selection is straightforward. If it is found available, the packets are delivered directly to the next hop according to the route information. The route selection steps are shown in Figure 4.9. The route update methods ensure the routing table already maintains the most optimised routes from the route update process. As a result, when every hop on the routes runs the same selection scheme, the packets should be delivered to the destinations. However, it is possible that the route has changed when the packets are sent. So although 'packet dropping' is unlikely, it is still possible.

**Step 1**

Search Node D from the Routing Table

**Step 2**

Forward to Next Hop

| Destination | GAW Mark | GAW State | Sequence Number | Metric | Next Hop | Expiry Timer |
|---|---|---|---|---|---|---|
| Node B | Null | Null | S180_NodeB | 1 | Node B | 15 |
| Node C | Null | Null | S206_NodeC | 1 | Node C | 10 |
| ... | ... | ... | ... | ... | ... | ... |
| Node D | Null | Null | S060_NodeD | 1 | Node D | 10 |
| Node E | GAWN | Identified | S288_NodeE | 2 | Node C | 15 |
| Node F | GAWN | Uncertain | S120_NodeF | 3 | Node C | 8 |
| Node G | GAWN | Identified | S300_NodeG | 3 | Node C | 15 |
| ... | ... | ... | ... | ... | ... | ... |

*Figure 4.9 Route Selection for Approachable Destinations*

***B. Route Selection to Unknown Destinations and Internet***

When the desired destination address is not in the routing table, the GAW routing method assumes it is in another domain or on the Internet. As shown in Figure 4.10, the route selection scheme begins with how to discover the route to such destinations. Since GAWNs are used as an approach to extend the search further to the other networks, route selection will choose one GAWN as the destination inside the wireless domain. Therefore, all these packets are forwarded to the GAWN. In this selection process, two routing parameters, the GAW state and the route metric are involved to decide which GAWN will be selected.

**Step 1** — Search GAWNs from the Routing Table

**Step 2** — Select GAWNs with the Highest GAW state

**Step 3** — Select GAWNs with the Lowest Metric

**Step 4** — Forward to Next Hop

| Destination | GAW Mark | GAW State | Sequence Number | Metric | Next Hop | Expiry Timer |
|---|---|---|---|---|---|---|
| Node B | Null | Null | S180_NodeB | 1 | Node B | 15 |
| Node C | Null | Null | S206_NodeC | 1 | Node C | 10 |
| ... | ... | ... | ... | ... | ... | ... |
| Node D | Null | Null | S060_NodeD | 1 | Node D | 10 |
| Node E | GAWN | Identified | S288_NodeE | 2 | Node C | 15 |
| Node F | GAWN | Uncertain | S120_NodeF | 3 | Node C | 8 |
| Node G | GAWN | Identified | S300_NodeG | 3 | Node C | 15 |
| ... | ... | ... | ... | ... | ... | ... |

*Figure 4.10 Route Selection for No- Approachable Destinations*

GAWNs are introduced to simplify the Internet connection task. So, when the packets are forwarded to the GAWNs, they still run the Ad Hoc routing method with GAWNs as their temporary destinations. The difference from the normal route selection scheme is that, the candidate destinations are a layer of GAWNs rather than one destination in the routing table. All GAWNs are listed for selection with their states and route metric. Wireless nodes need to select one of them as the destination to forward the data packets to. However, the sequence numbers of each route are generated by the destination nodes so they cannot be used to compare the chronology of these routes. Therefore, the GAWN's states are employed to distinguish between them. All GAWNs with the same states have the same level of abilities to provide the connection service. Based on this definition, the source picks up the GAWNs with highest states and applies the shortest path first algorithm among them.

GAWNs with identified state have the highest priority since they are those most recently updated and have the most possibility to provide Internet connectivity. The route selection scheme chooses from the identified GAWNs with the shortest route metric. In the case when no GAWNs have identified state, the route selection scheme will list all the GAWNs with uncertain state. From the definition of GAWN states, the 'uncertain state GAWNs' may well have the Internet connection. When the source has to choose from the uncertain GAWNs, it also chooses from those with the shortest route metric.


| Destination | GAW/IG Mark | ... | Sequence Number | Metric | Next Hop | Expiry Timer |
|---|---|---|---|---|---|---|
| ... | ... | ... | ... | ... | ... | ... |
| Node M | IG | ... | S060_NodeM | 1 | Node M | 10 |
| ... | ... | ... | ... | ... | ... | ... |

*Figure 4.11 Route Selection from GAWN to IG*

After the packets reach the GAWN, the routing inside the MANET is over. The packets are forwarded to the Internet through the GAWN. Shown in Figure 4.11, GAWN has the routing information for all IGs within its range. If there is more than one IG in the GAWN's routing table, a random selection will be made.

The IGs use wired routing protocols to deliver the packets on the Internet. If the destination is on the Internet, the packet delivery is straightforward. When the destination node is in another wireless network and happens to get connected with the Internet through other GAWNs, the packets can follow the path wireless-wired-wireless to reach the destination. As a result, the route discovery is extended through the Internet.

### 4.2.7 GAW Load Balancing

The data delivery method of GAW is derived from DSDV, which uses the shortest path first algorithm to choose the routes and maintain them without any load-balancing scheme. It is clear that the route selection method of GAW forwards all the packets to unknown destinations or other domains to the layer of GAWNs increasing their traffic loads. Without load balancing, it may be possible that the loads on some GAWNs consume too many resouces whilst the others do not carry much traffic. To solve this problem, a GAW load-balancing scheme is designed in the GAW route selection method.

As previously stated, the GAW routing method uses the distance vector and the shortest path first algorithm, and the destination's routing information has already been optimised in the route update process. The load balancing of the GAW route selection scheme is applied when selecting the route to Internet, where the layer of GAWNs changes the single destination of an IG into multiple destinations of GAWNs. The GAWNs are classified by GAW state, which reflects the stability of the Internet connection they can offer. Therefore, all GAWNs with the same GAW state provide the same connection stability. The multi routes in the routing table provide the foundation on which to apply load balancing.

Since the GAW mark and GAW state have been used to create the multi routes options, the routing metrics left in the GAW routing table are those from the DSDV routing parameters; including sequence number and distance metric. In a highly dynamic MANET, the correctness of these two parameters depends on the probability of link breakage between nodes. The sequence numbers are generated by each individual destination so that they cannot be used to compare with each other. Thus, it cannot be used in the route selection process. However, the distance metrics of each route can be used. The probabilities of link breakage to each route with the same distance metrics are the same. As a result, a uniform distribution method can be used directly on the routes with the same distance metrics.

For each data packet, the source node can choose from any of these GAWNs of the same distance metric with a uniform distribution. This distribution ensures that each qualified GAWN receives equal loading. In the GAW routing method, the load balancing is done based on each packet. Along the route to the chosen GAWN, it may change again if the routing metric changes. As a result, both the load on the GAWNs and the load on the routes to GAWNs are well distributed. The QoS for MANET routing is out of the scope of this thesis but will be considered as part of the future development.

Figure 4.12 shows an example. When a request is made, 3 different GAWNs provide the same route metric to the same IG and all have the state of 'identified'. The source node can choose from any of them and still deliver the packet to the Internet. Without the load-balancing scheme, one route to the IG may be used more often than the others, leaving network resources wasted. In the example, by applying GAW load balancing, each GAWN carries nearly the same amount of traffic.

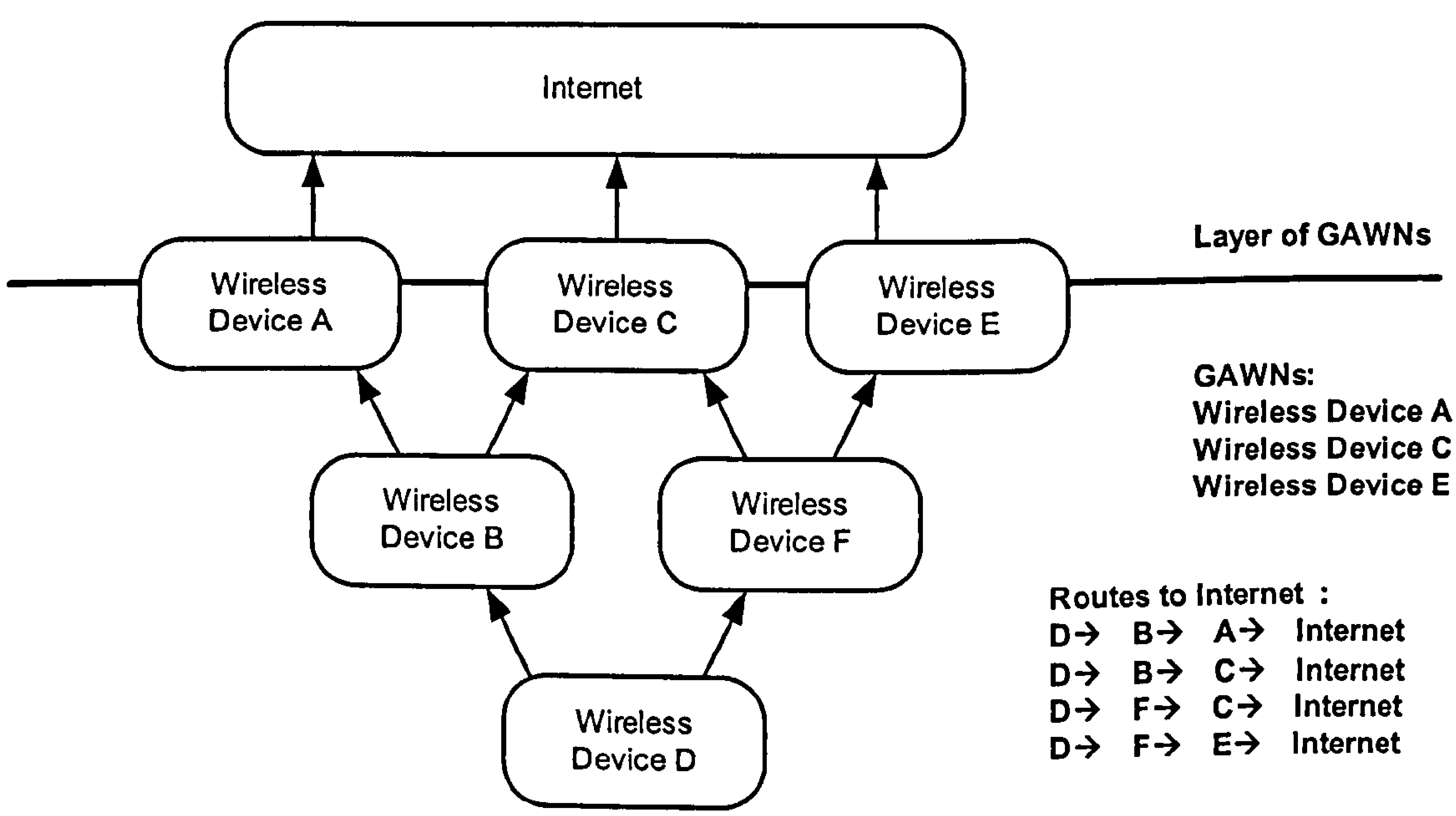



*Figure 4.12 An Example of GAW Load Balancing*

### 4.2.8 Link Breakage and Packet Dropping

Broken links occur frequently in Ad Hoc Wireless Networks and will not be discovered by a proactive routing scheme until the update messages containing the 'broken link broken news' are received. In the GAW routing method, the broken link is detected by using the expiry timer set to make a quick response to a broken link in wireless networks for each destination in the routing table. For a normal wireless node, the timer is set to start when an update message is received from the neighbour. If there are no new update messages coming from this neighbour after the timer has expired, the link between these two nodes is assumed to be broken.

After the broken link is detected, the node sends a trigger update message to inform others of this change. All broken link messages are forwarded immediately so that all network members receive them and learn about the route changes. As discussed in section 4.2.2, the GAWN maintains an expiry timer for the IGs. If the timer has expired and no new broadcast is received from IGs, the GAWN changes its state and sends a GAW cancellation message to inform others about the change. The state changes are sent with the update messages to the network.

To compensate for the unknown route information due to a broken link, the routes to GAWNs are more frequently updated. When the communication request is made to a destination with a broken link, the packets are delivered to the GAWNs to extend the route discovery period.

However, if the broken link is not discovered in time, the packets are dropped due to the inaccurate routing information. For example, if a route showing in the routing table is changed right after the update process, the nodes cannot discover it until the timer has expired or a new update message is received. Therefore, a packet that goes to any destinations using that route may be wrongly delivered and thus dropped. Packet dropping may also happen if there is still no route information available after having extended the route discovery period. Protocols in other layers such as TCP can be used to avoid packet dropping due to these reasons.

## 4.3 Internet Connection Using GAW Technology

### 4.3.1 Gateway Discovery Overview

As discussed in 4.1.2, IGs can provide Internet connectivity for the wireless terminals in a MANET. The process of configuring the network connectivity can be initiated by the IG, by the mobile terminal or by mixing these two, giving rise to proactive, reactive and hybrid gateway discovery methods [88]. All these methods, shown in Figure 4.13, have their most suitable scenarios. To achieve the best performance of the Internet connection, the routing protocol and the gateway discovery method have to work closely together. The following sections explain these three methods and their advantages and disadvantages. The gateway discovery method used in the GAW routing method is described in 4.3.2-4.3.8.

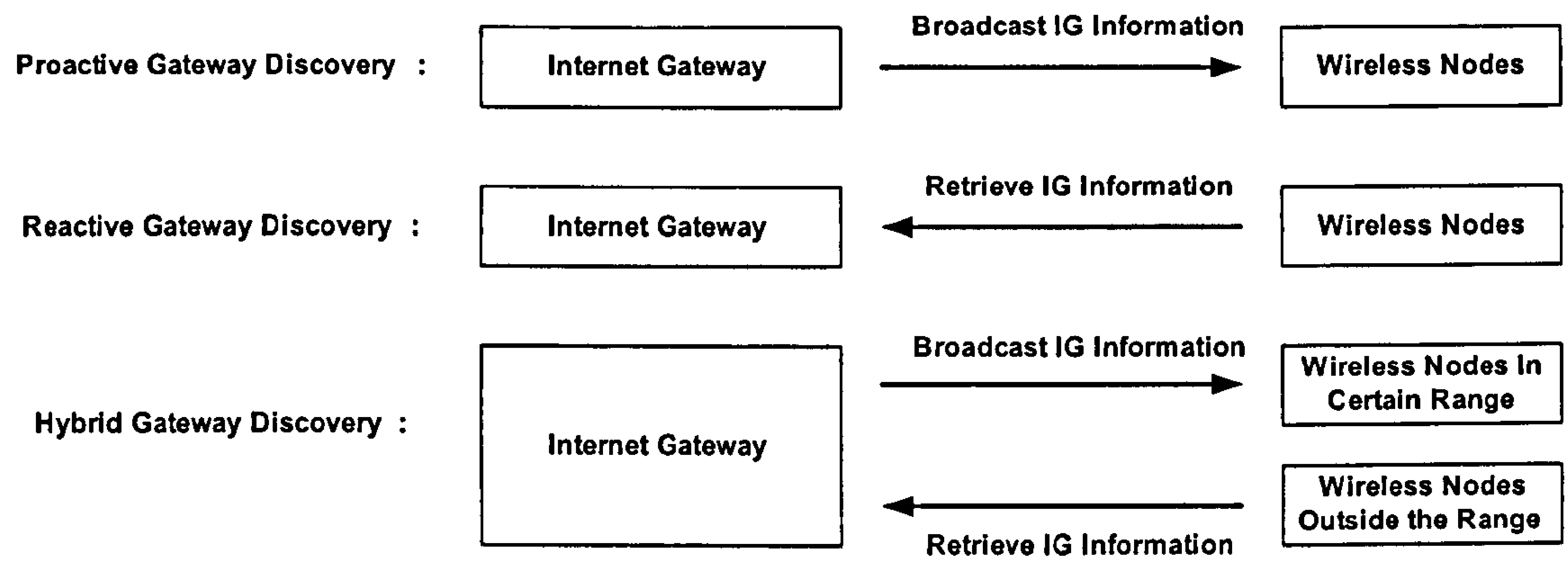



*Figure 4.13 Internet Gateway Discovery Methods*

### *A. Proactive Gateway Discovery*

In this approach, the IG initiates discovery by periodically broadcasting a gateway advertisement message, according to a carefully chosen timer. This has to be frequent enough to enable new wireless network members to be acknowledged when the network topology changes frequently but not so frequent that the network is flooded with unnecessary advertisements. All mobile nodes within the wireless propagation range of the IG receive the advertisement, when mobile nodes that do not have a route to the IG create a route for it in their routing tables. Those mobile nodes that already have a route to the IG, update their route for any changes. The advertisement message will be forwarded to the other mobile nodes, and the update process is repeated hop by hop so that all the nodes within the wireless domain may know of the existence of the IG. The advantage is that all the nodes can immediately find out the route to the IG from their routing table, which avoids unnecessary delay. The disadvantage is that the IG advertisement periodically floods the whole wireless network.

*B. Reactive Gateway Discovery*

Unlike the proactive gateway discovery method, a mobile node initiates the reactive gateway discovery by requesting information from the IG, so that advertisement messages are sent only when a mobile node needs information from the IGs. By doing this, the wireless network avoids being flooded by the periodic advertisements but there may be a delay in receiving the IG information after it has been requested. Also, the network load increases as such requests increase.

*C. Hybrid Gateway Discovery*

Hybrid gateway discovery is a combination of the two approaches above, used to minimise the disadvantages of proactive and reactive gateway discovery. For mobile nodes in a certain range around a gateway, proactive gateway discovery is used. Mobile nodes residing outside this range use reactive gateway discovery to obtain information about the gateway.

## 4.3.2 GAW Gateway Discovery

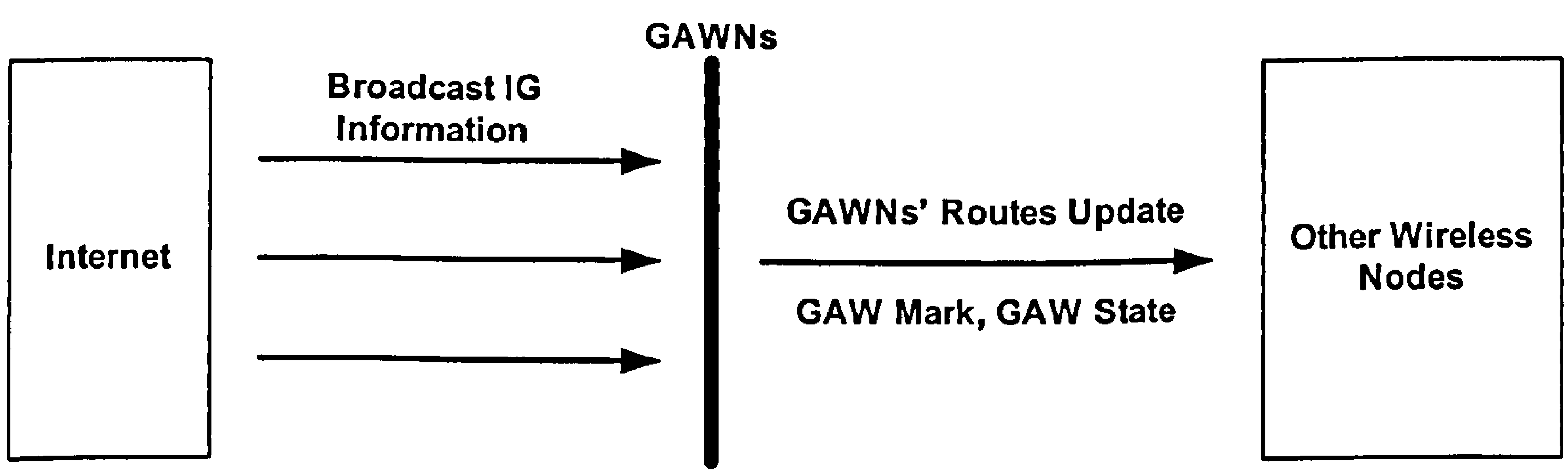



*Figure 4.14 GAW Route Discovery*

Described in Figure 4.14, the GAW technology employs the proactive gateway discovery method with some modifications. The frequently broadcast messages from IGs are received by GAWNs on which the connection channel is maintained. Instead of sending out the IGs' information to the rest of the network, GAWNs identify themselves as the layer with Internet connection ability. The Internet connection information is forwarded to the rest of the wireless network within the normal route update messages of GAWNs.

With the GAWN's functions, this method simplifies the gateway discovery task into two steps. GAWNs are normal wireless nodes in the MANET, their routing information has been in the routing table of other nodes as one of the destinations. Therefore, the gateway discovery has began routing to the GAWNs in the MANET and GAWNs to Internet communication. This not only stops the flooding of IGs broadcast information but also keeps the independency of the MANET.

In the GAW gateway discovery process, the IGs broadcast period and IGs expiry timer needs to be carefully considered. A more frequent IGs broadcast period and a shorter IG expiry timer can be chosen if the wireless nodes' mobilities are high, and vice versa. When the GAWN is a wireless node with wired connection, it does not need the expiration timer but leaves the connection state for hardware detection. By employing the GAW gateway discovery method, the wireless nodes only need to check if there are GAWNs within approachable range for Internet connection purposes.

### 4.3.3 GAW Internet Registration

Data exchanges between the IGs and GAWNs provides IGs with very detailed information for the attached MANET, including the network size, all approachable wireless nodes and other routing information. This is called registration because only the GAWNs send data to the IG. The GAWNs send their entire routing table to IGs as they do for all wireless neighbours. As a result, all the destinations, which are approachable by these GAWNs, can have their information registered on the Internet. The registration offers the essential routing information of wireless nodes when they are requested from the Internet.

GAWNs can discover the routes to the Internet but they are still wireless nodes. GAW technology uses the layer of GAWNs as the intermediary between two networks. Therefore, the IGs do not broadcast any routing information back to GAWNs, including the information related to the wireless nodes in MANET. It is possible that two wireless nodes, which are out of reach in the wireless domain, register themselves with different IGs, shown in Figure 2.7. Therefore, they can build the communication between themselves through wireless->wired->wireless channel. However, in order to leave the Ad Hoc routing in an independent state, the routing tables of wireless nodes only maintain the routes to other nodes, which are available inside the MANET.

### 4.3.4 GAW Internet Connection Overview

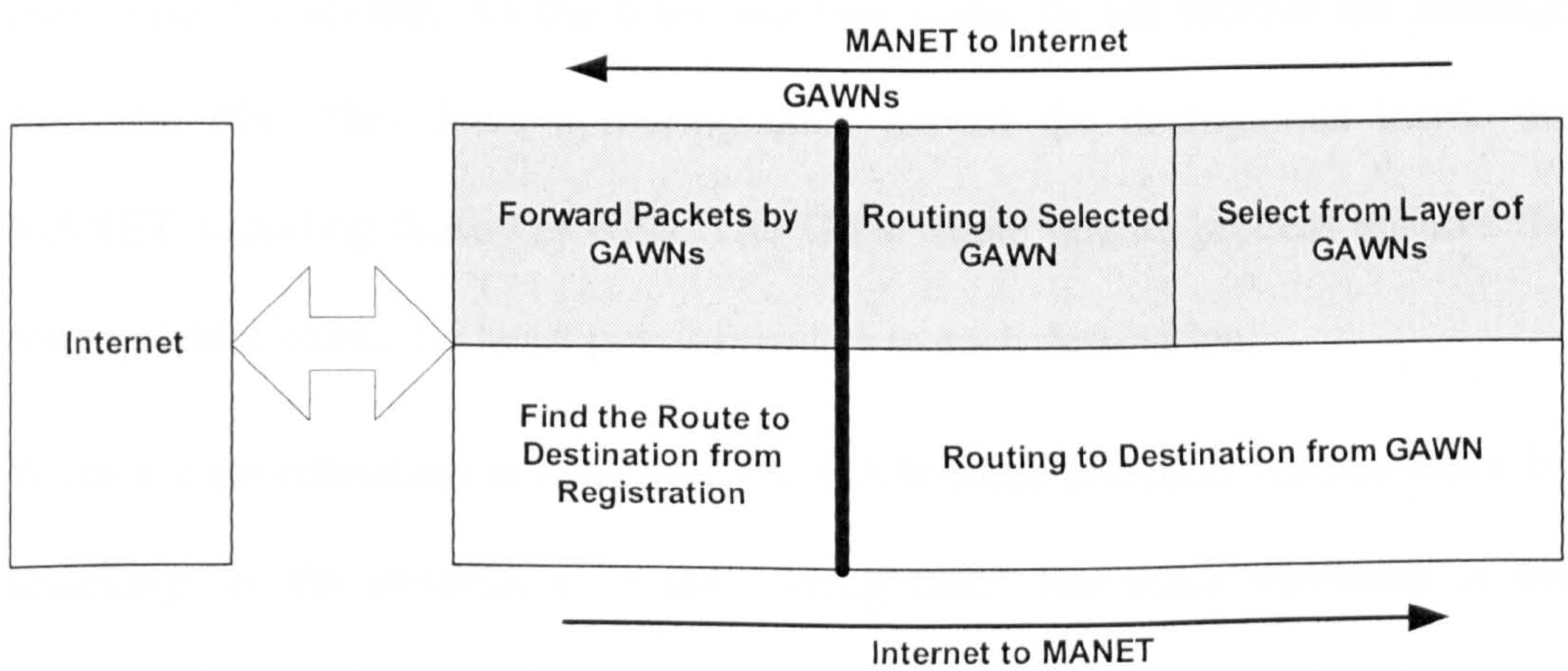



*Figure 4.15 GAW Internet Connection Overview*

After defining the GAWNs, the communication between the Internet and the MANET has become a two-step process as shown in Figure 4.15. One step is the GAW routing inside the MANET, carried out by the GAW routing method in the MANET. The other step is the communication between IGs and GAWNs. This connection is maintained by the GAW gateway discovery method. Through the data exchange from GAWNs to the Internet, the wired nodes can find out the route to any approachable wireless nodes. The following sections describe the communication process between nodes on the Internet and the MANET using the GAW routing method.

### 4.3.5 From MANET to Internet

In the MANET, wireless nodes have been catalogued into two groups, GAWNs and normal wireless nodes. GAWNs discover the route to the Internet and maintain it in their routing table, for example, the IGs' routing information. This information is not included in any route update message to the wireless network. Instead, the GAW mark and GAW state is attached to the GAWNs' routes when they make the update. All the other wireless nodes do not receive the message from the IGs. They have a routing table for all the destinations inside the MANET including those GAWNs. The GAW route update process ensures the routing tables stores the latest possible routes to each destination.

When a communication is requested, the GAW route selection scheme starts by searching for the destination in the routing table. For those addresses in the routing table, packets are delivered directly. If the address is not found or is in another domain, the route selection scheme assumes that external route discovery is needed. However, before the packet reaches the GAWNs, the routing scheme is still inside the MANET. Route selection takes the layer of GAWNs as the final destination and delivers the packets by applying the GAW load-balancing scheme to optimise the network traffic. This process is repeated hop by hop until the layer of GAWNs is reached. Note that due to the GAW load-balancing scheme, the final GAWN may not be the same one as that used by other data packets from the same data source.

After the GAWN has received the data packet, it recovers the original destination address and forwards the packet to the IGs. From this point, the communication enters the Internet. A wired routing protocol takes over the route discovery and decides what to do next.

### 4.3.6 From Internet to MANET

On the wired network side, nodes closest to the wireless network may declare themselves as IGs by periodic announcements to the wireless domain. The other wired nodes do not send advertisements and therefore are connected to the IG and to each other via optical lines. Diverse routing protocols are used to connect nodes in wired networks, but the position of the IG and the other wired nodes are fixed.

The layer of GAWNs offers a stable interface to the Internet for a dynamic MANET. All the necessary routing information about the wireless domain can be obtained for IGs from GAWNs. As a result, although the actual identities of GAWNs are changing from time to time, the layer of GAWNs continually provides routes to the wireless network. Therefore, the nodes on the Internet get to know all the approachable destinations in the wireless domain without sending any probing messages into it.

When a wired node initiates a communication to a wireless terminal, it first forwards the data packet to the IGs using a wired routing protocol. The data packet then goes through the GAWN layer into the wireless network with the route information for the packets. The GAW routing method fulfils the Ad Hoc wireless routing to the desired destination within the wireless network.

The two-way communications are not identical. The GAW load-balancing scheme is involved in wireless to Internet communication and the optimisation of the wired routing protocol is out of the scope of this thesis.

### 4.3.7 Extended Wireless Communication

The wireless->wired->wireless communication becomes possible as an extended form of wireless communication using the GAW routing method. Although it looks like the communication type for an infrastructure WLAN, it uses completely different routing methods.

In an infrastructure WLAN, the base stations (or IGs) are in charge of all the communications between any wireless nodes. In other words, communications between any two wireless nodes have to go through the base stations. Therefore, even if two nodes are within reach of each other, they still need to find a base station to set up any form of communication.

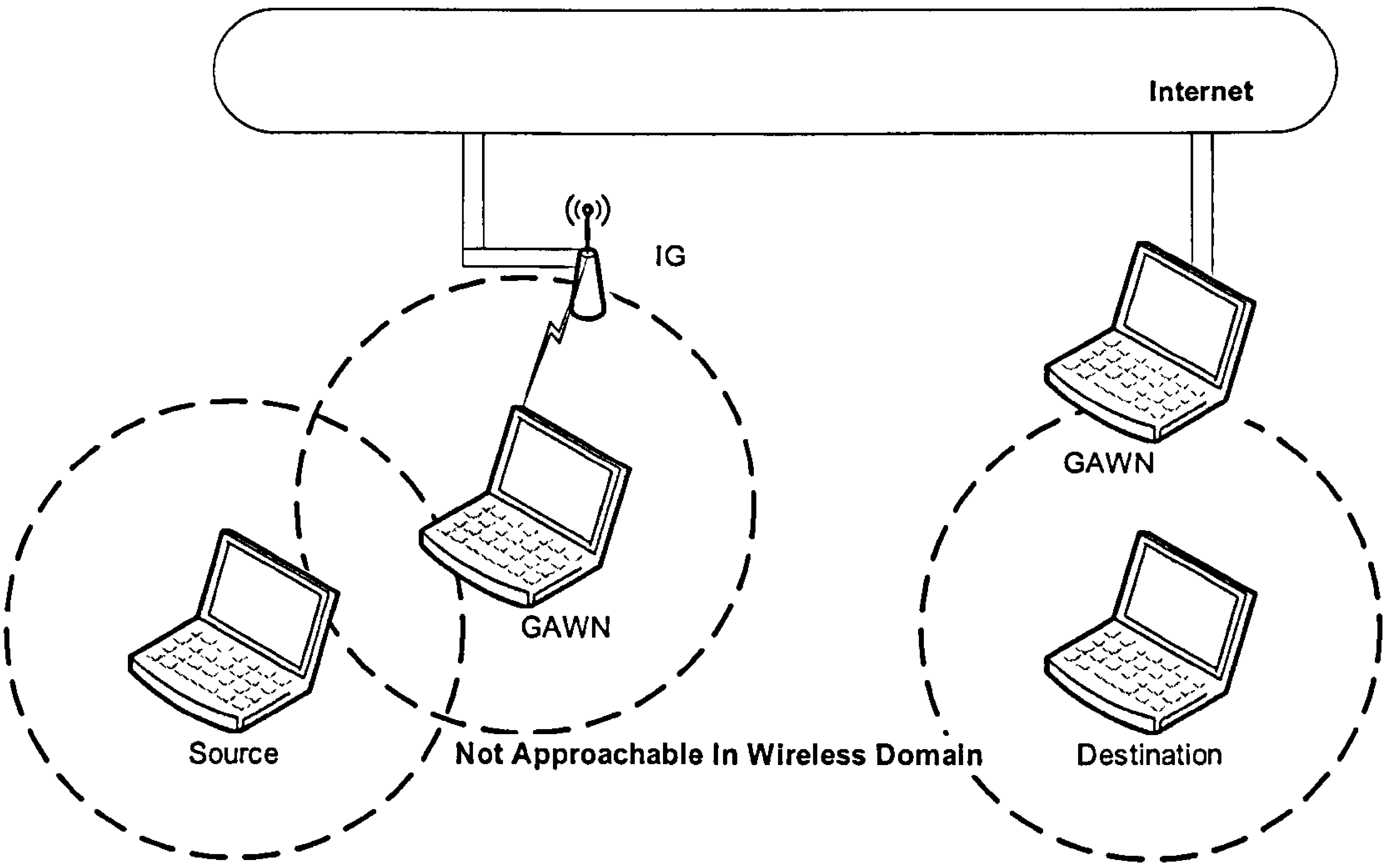



*Figure 4.16 Wireless-Internet-Wireless Communications*

In the MANET, using the GAW routing method, the wireless->wired->wireless communication becomes the extended wireless communication as the result of extended route discovery from the Internet. Figure 4.16 shows an example of this extended wireless communication where the IG is involved only when the route discovery has failed in the wireless network. In the GAW routing method, when the wireless link becomes available in the wireless domain, the IG will no longer be used.

# Chapter 5 Simulation of MANET and Internet Communications



## 5.1 Network Simulator 2

Network Simulator 2 (NS2) [101] is used in this thesis as the simulation tool for comparing the routing performance of different MANET to Internet methods. NS2 is an open source code, discrete event simulator for networking research. It provides substantial support for the simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. NS2 is the result of an on-going effort of many researchers. Currently NS2 development is supported through DARPA [72] with SAMAN [102] and through NSF [103] with CONSER [104], both in collaboration with other researchers including

ACIRI [105]. Although NS2 is not a finished and polished commercial product, it provides reliability and is generally agreed to be one of the best simulators for the study of MANET routing protocols. NS2 provides the implementations for many MANET routing protocols such as DSDV, AODV and DSR. The wireless network models such as physical, data link and MAC layer in NS2 were implemented and supported by the Monarch project [106]. Many well cited published works relating to MANET use NS2, including the routing performance analysis for MANET [107, 108]. The simulator used for the experimental work for the thesis is NS-2.1b9a with the general simulation scenario' setting commonly used for MANET simulations.

NS2 is written in C++ with the OTcl interpreter as a command and configuration interface. The C++ part is used to implement the detailed protocols and the OTcl part is used to configure the simulation scenarios. NS2 can be downloaded free from the Internet [101] with a supportive manual [109] and tutorials to explain the links between C++ and OTcl as well as further information about the network components and so on. NS2 tutorials of can also be found in Marc Greis' tutorial [110] and Jae Chung & Mark Claypool's "NS by example" [111].

NAM [112] is an animation tool for viewing network simulation traces and real world packet traces. It supports topology layout, packet level animation and various data inspection tools. The screen shots used in this chapter for simulation scenarios were taken using the NAM generated topologies.

NS2 uses trace files to save all the data for the simulation. The trace file keeps records for all information for wireless and wired communication according to the protocols used. The trace file formats used in the simulations for this thesis were DSDV and AODV for wireless communications [113].

The GAW routing method is developed based on the C++ models for DSDV which are created by other NS2 researchers [101]. The modifications include additional routing table parameters, new route update messages, new route update process and new route selection process with load balancing. The GAW routing classes are derived from the DSDV routing classes. A new routing protocol agent for GAW is also created in NS2 to support the routing protocol.

# 5.2 Simulations for Internet Connections with NS2

## 5.2.1 Overview

To compare the Internet connection performance of Ad Hoc routing protocols, simulations for DSDV, GAW and AODV are performed with NS2. The IG discovery methods are introduced based on the NS2 C++ protocol module for DSDV and AODV. In [89], both proactive and reactive gateway discovery methods are designed for AODV. They are used in this thesis to compare the performance with other methods, DSDV and GAW, for MANET to Internet connection. The GAW routing method with the proactive gateway discovery method is developed from the DSDV model, with GAW routing inside the MANET. The DSDV routing protocol has been modified to use the proactive gateway discovery method in GAW. This section will introduce the work relevant to these methods and their functionalities. The key parameters of each connection method will be shown and more details concerning the setting up of each protocol model can be found in NS-2.1b9a.

## 5.2.2 Internet Connection with AODV

### *A. Internet Gateway Discovery Method*

Ali Hamidian [89] investigates the implementation of proactive gateway discovery and reactive gateway discovery in his master's thesis according to the Internet draft 'Global connectivity for IPv6 Mobile Ad Hoc Networks' [88] using NS2. To compare with the GAW routing method, both gateway discovery schemes for AODV were used in this thesis. The IG is employed to connect the Internet and the MANET, and is defined with a common network address of ALL_MANET_GW_MULTICAST. Wireless nodes in MANET all need to discover the IG when a request is made. Figure 5.1 shows the processes of the two gateway discovery methods.

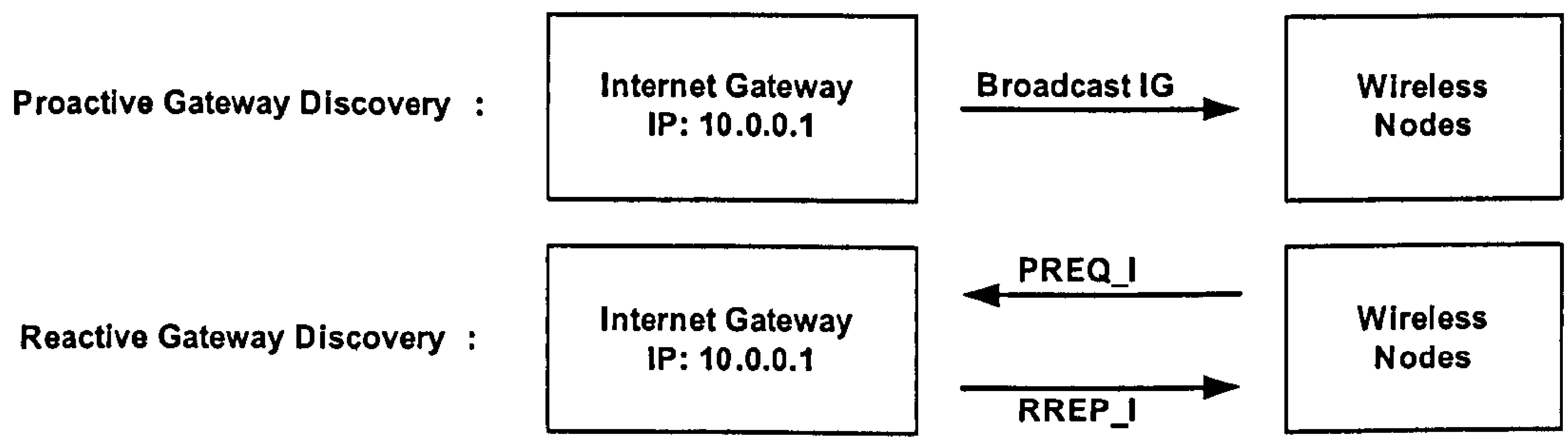



*Figure 5.1 Gateway Discovery methods for AODV*

The proactive gateway discovery for AODV is described as follows. The IG initiates the gateway discovery process with a periodical advertisement message, where the interval is defined as ADVERTISEMENT_INTERVAL. When wireless nodes receive the broadcast message, they check their currently maintained route entries for it. If the route to the IG has not been heard, the nodes will update the route information directly. For those nodes that already have the route, the new entry is updated. Next, the message is broadcast to the neighbours and so on. In this work, a scheme to prevent duplicate broadcast from one node is introduced. However, like all the proactive approaches, the broadcasts from the IG may flood the wireless network. The AODV, with the proactive gateway discovery method, is named as *AODV-P* in the simulations. In section 5.4, the ADVERTISEMENT_INTERVAL is set from 5, 10, 20, 30, 40, 50 and 60 seconds to have an overall picture of the influence of the IG broadcast interval on routing performance.

Reactive gateway discovery is also implemented and referred to as *AODV* since the routing protocol itself also uses the reactive route discovery method. In *AODV*, the wireless node initiates the gateway discovery by sending a PREQ_I to the common IG's address. All the intermediate nodes will forward this request by broadcasting it further. When the IG receives the request, it sends a unicast message RREP_I with its real IP address to setup the routes for the wireless nodes. The whole process is done in the same way as for a normal AODV route discovery. The advantage of *AODV* is that the request to the IG is only sent when it is demanded, and since AODV is a reactive routing protocol, it can be directly developed from its own routing scheme. However, the disadvantage is that since finding an IG is the only way to build the Internet connection, discovering an IG may result in increasing the loads of forwarding mobile nodes, especially the nodes close to the IGs. The reactive gateway discovery method does not respond to the changes of IG broadcast interval. As a result, it will give a constant performance to these changes.

***B. Communication between MANET and Internet***

With both *AODV-P* and *AODV* implemented, the communication from MANETs to the Internet becomes available. In *AODV-P*, the routes to the IG are updated by the broadcast message. In *AODV*, RREQ_I is used to discover a route to the

IG. Key parameters for *AODV-P* and *AODV* are shown in Table 5.1. They are selected from the specification of AODV [84, 85]. Apart from the gateway discovery method, AODV routing protocol is used to handle the routing inside the MANET. Once the route is built, the source nodes maintain the route and start the communication on it until it is broken. An alternative route can be used to continue the communication.

*Table 5.1 AODV routing protocol parameters*

| Parameter | Value |
| --- | --- |
| ACTIVE_ROUTE_TIMEOUT | 10 Seconds |
| RREQ_RETRIES | 2 |
| TTL_THRESHOLD | 7 |
| MAX_RREQ_TIMEOUT | 10 Seconds |
| GWINFO_LIFETIME | 10 Seconds |

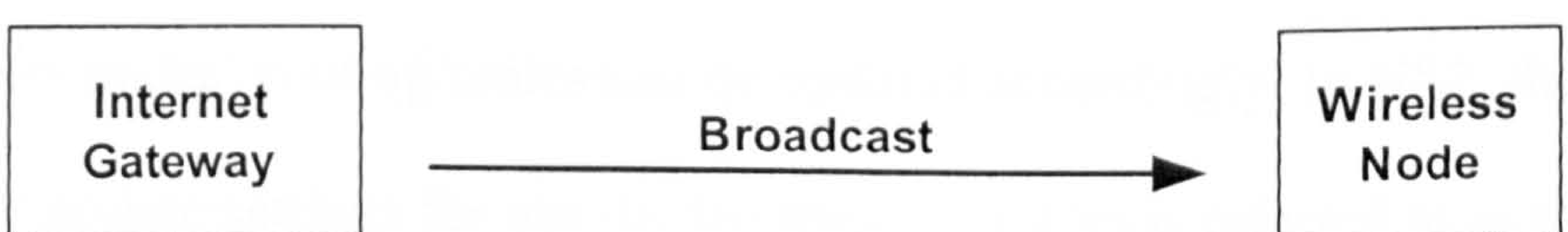
One of the most important issues that need to be considered in the implementation is the case of an unreachable IG. In the original AODV routing protocol, when a RREQ message is broadcasted for a destination and no RREP is received, an expanding ring search technique is used to search for a large network area. A TTL (time to live) value is set to the RREQ with a max threshold. If no reply is received, RREQ can be resent with RREQ_RETRIES times, the destination is notified as unreachable if all these fail. However, the unreachable gateway problem is not covered in any proposed work. As implemented in [89], for both *AODV-P* and *AODV*, the wireless node broadcasts the RREQ_I message until a gateway is found. This method increases the delivery ratio while the delay time by the gateway discovery can be significantly high. The overall performance analysis will be presented in section 5.4.

The communications from the Internet to the MANET did not being studied before in [88, 89] for AODV. In fact, as AODV is a reactive routing protocol, the wireless nodes do not know the locations of any other nodes unless there are currently maintained routes to them. The nodes on the Internet usually do not know where the destinations are when they are outside their routing table. This is true even if the source node can tell by the addresses that the destination nodes belong to the wireless network, since they still do not know which IG among a number of others can be used; or has a connection with the destinations. This is also a problem for the wired node or IG who has to utilise the reactive routing protocol to discover the destinations in the MANET.

Therefore, to support Internet to MANET communication, an extra register scheme for wireless nodes using the reactive protocol may be needed for wireless nodes to register their locations with the IG. To do this, a proactive register scheme will have to be added to the reactive routing protocol. Currently, no such implementation exists. As a result, it was not considered to try the Internet to MANET communication in this thesis.

## 5.2.3 Internet Connection with DSDV

### *A. Internet Gateway Discovery Method*




| Destination | Base Station | Metric | Sequence Number | ... |
|---|---|---|---|---|
| ... | ... | ... | ... | ... |
| Node C | Null | 1 | S206_NodeC | ... |
| ... | ... | ... | ... | ... |
| Node D | Yes | 2 | S060_NodeD | ... |
| ... | ... | ... | ... | ... |

*Figure 5.2 Implemented DSDV Internet Gateway Discovery*

In NS2, DSDV supports wireless-cum-wired communications by pre-defining the base stations in the OTcl simulation configuration files for all wireless nodes [110]. By doing this, the requests to other networks or unknown destinations are configured to be forwarded to base stations. The base stations are defined with the same function as a wireless node with a passive route updating method. All wireless nodes update the routes to base stations by receiving the update message from them. However, this definition limits the MANET to Internet connection to some fixed base stations. While the wireless nodes are on the move, new connections from other base stations may be demanded but will fail to be recognised without pre-definition.

In order to perform seamless roaming, the proactive gateway discovery method used for GAW has been implemented for DSDV. The base stations are defined as IGs without pre-defining them in the configuration files. The IG is set to periodically broadcast messages with its route to the wireless network. As shown in Figure 5.2, when the wireless nodes receive this update message, they update their routing table as if the IG is defined as a base station.

The DSDV routing protocol is used to forward and maintain the routes' information includes IG's. Since the IG information is periodically sent out, the wireless nodes' routing tables can be updated accordingly. In NS2, there are two DSDV update settings for use. In this thesis, the first is referred to as the *DSDV-S*, where each new sequence number initiatives a trigger update through the network. This method has a good response to network changes since all the new update messages, including the IG's broadcast messages, are forwarded immediately. However, the network is flooded by these messages, resulting in a heavy routing overhead. The second one does not make a trigger update for each new sequence number and is referred to as *DSDV* in this thesis. The IG's information is also updated as if it is one of the wireless nodes. With less routing overhead on the network, this *DSDV* setting has a very slow response to network changes and the performance is low. An analysis for these two DSDV settings is discussed in [108].

As to the proactive gateway discovery, *DSDV-S* updates the routing table and forwards each broadcast from the IG immediately, whilst *DSDV* only forwards them once for the first time they are received and updates them as one of the destination afterwards. Both settings have been implemented in NS2 and their performances are compared in section 5.4.

***B. Communication between MANET and Internet***

*Table 5.2 DSDV routing protocol parameters*

| Parameter | Value |
|---|---|
| Periodical Update Interval | 15 Seconds |
| Route Expiry Timer | 3 * Periodical Update Interval |
| # of Changes for a new Periodical Update | 3 |
| IG Broadcast Interval | From 5 to 60 Seconds |

Some key parameters of the implemented *DSDV-S* and *DSDV* are shown in Table 5.2. These parameters are selected based on the DSDV [90] protocol specification. The DSDV routing protocol in NS2 assumes that the route needs to go through an IG if the destination is in a different domain to the source node. So, when a request to the Internet is made, the source node searches for the IG from its routing table and forwards the packets with the selected route. The DSDV routing protocol only queues the packets to unknown wireless destinations in the same wireless domain. As a result, if the route to the IG does not exist, the packet is dropped directly.

The DSDV routing protocol was extended with the IG receives the routing table update message and update for the destinations in the MANET, so that Internet to MANET communication becomes possible with DSDV. Currently, there are no instructions on how to do it. In the implementation in this thesis, the same scheme used in the GAW routing method has been introduced to *DSDV-S* and *DSDV* respectively, with each approachable wireless node is stored in the routing table of an IG, from where nodes on the Internet know through which IG the route to the destination wireless node can be found.

As DSDV with proactive gateway discovery method is implemented, the IG's broadcast interval will affect the routing performance. By changing the IG broadcast timer from 5, 10, 20, 30, 40, 50 and 60 seconds, an overall picture of the routing performances is given in section 5.4.

### 5.2.4 Internet Connection with GAW

*A. Internet Gateway Discovery Method*

As introduced in section 4.3.2, the GAW routing method uses the proactive gateway discovery method. In NS2, a wired node is defined as the IG with periodical broadcast of its routing information with the IG mark to the wireless network. Unlike the implementation for DSDV, in GAW, the IGs are not accepted as base stations by all wireless nodes. Since only the GAWNs receive their broadcasts, they are stored in the GAWNs' routing tables as IG with an IG Mark in the GAW/IG mark place. The GAWNs routing information is updated by wireless nodes as one of the destinations in the Ad Hoc domain and will be called when requests to the Internet are demanded. The two step Internet connection is used from the GAW routing method.

***B. Communication between MANET and Internet***

Section 4.3 has described the algorithm for the communications. When implementing the GAW routing method with NS2, the unreachable IG case does not exist since all the communications are treated as Ad Hoc routing until they reach the GAWNs. In fact, when there are GAWNs in the node's routing table, the routes to the IG are assumed to exist unless the routing information is wrong. The packets being deliverer to GAWNs are going direct to the IG or are dropped. When there are no GAWNs in the routing table, wireless nodes queue the packets to unknown wireless destinations and drop those for the Internet.

*Table 5.3 GAW routing method parameters*

| Parameter | Value |
|---|---|
| Periodical Update Interval | 15 Seconds |
| Route Expiry Timer | 1 * Periodical Update Interval |
| # of Changes for a new Periodical Update | 3 |
| IG Expiry Timer | 1 * IG Broadcast Interval<br>Or 1 * Periodical Update Interval |
| GAWN's State Change Timer | 1 * IG Broadcast Interval |
| IG Broadcast Interval | From 5 to 60 Seconds |

Some key parameters are shown in Table 5.3. These parameters are selected based on the DSDV [90] and experimental works of GAW routing method. Simulations have been carried out to compare GAW with *AODV-P*, *DSDV-S* and *DSDV* on communications from MANET to Internet. Works for Internet to MANET communication were also done for *DSDV* and GAW. The possible extended form of wireless communication was investigated as well. The results will be shown in section 5.3.

## 5.3 General Simulation Setup

### 5.3.1 Simulation Scenario

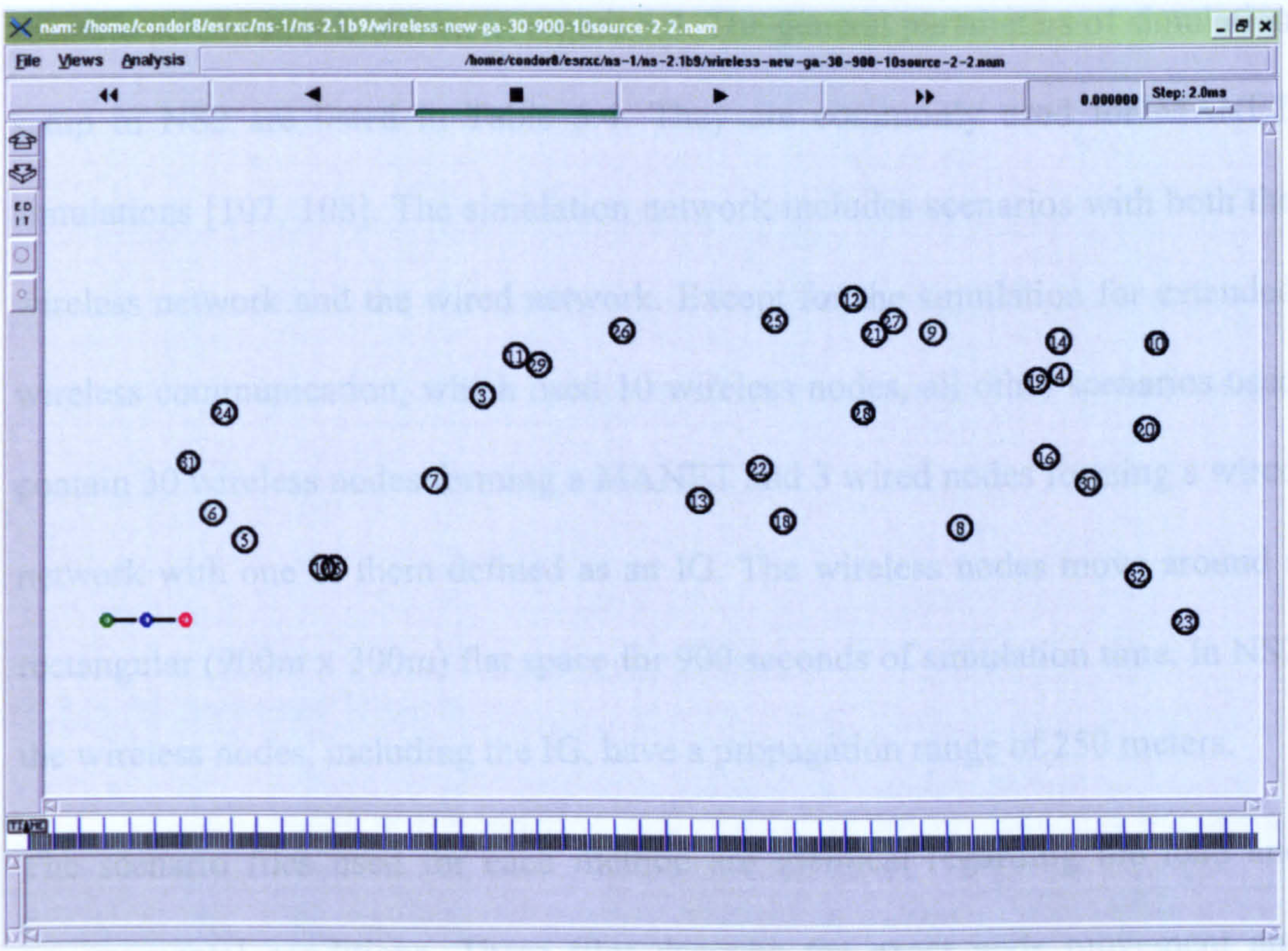



*Figure 5.3 Simulation Scenario Screen Shot*

*Table 5.4 General Simulation Setup Parameters*

| Parameter | Value |
|---|---|
| Topology Size | 900m X 300m |
| Wireless Transmission Range | 250m |
| Number of Wireless Nodes | 30 / 10 |
| Number of Wired Nodes | 3 |
| Number of IG | 1 |
| IG Position | (0,0) (200,100) (450,150) |
| Traffic Type | Constant Bit Rate |
| Packet Rate | 1 Packet / Second |
| Packet Size | 64 Byte |
| Source Start Time | Between 100 and 200 seconds |
| Pause Time | 0,30,60,120,300,600,900 |
| Max Speed | 1m / second |

The target of the simulation work is to investigate the performance of the GAW routing method and compare its ability to provide Internet connection with other methods under different network conditions. An example of the simulation scenario screen shot is shown in Figure 5.3. The general parameters of simulation setup in NS2 are listed in Table 5.4. They are commonly used for MANET simulations [107, 108]. The simulation network includes scenarios with both the wireless network and the wired network. Except for the simulation for extended wireless communication, which used 10 wireless nodes, all other scenarios used contain 30 wireless nodes forming a MANET and 3 wired nodes forming a wired network with one of them defined as an IG. The wireless nodes move around a rectangular (900m x 300m) flat space for 900 seconds of simulation time. In NS2, the wireless nodes, including the IG, have a propagation range of 250 meters.

The scenario files used for each method are identical regarding the load and environmental conditions. These files describe the exact node movement and time at which each change in motion is to occur. There are 70 pre-generated different scenario files with varying movement patterns, traffic loads and IG locations, and implementations are run against each of these scenario files. Since each connection method is simulated in an identical fashion, their performance results can be directly compared.

### 5.3.2 IG's Position

In these simulations, one wired node worked as the IG. For the GAW routing method, since the layer of GAWNs takes over the connection task, it does not matter for wireless nodes to discover how many IGs there are in the network.

They only know how many GAWNs are available to use in the MANET. Instead of increasing the IG's number, the simulations investigate the effects from different positions of IG. In the simulations, the IG was distributed at (0,0), (200,100) and (450,150) to investigate the case where the IG is far away from the wireless nodes movement area to the very middle of that area. The IG at the edge of network means fewer GAWNs and longer routes from sources to GAWNs. The IG in the middle of the network will result in more GAWNs and shorter routes from sources to GAWNs. These settings combine both IG quantities and positions in the scenarios for the simulations.

### 5.3.3 Movement Model

The node movement in the simulation is according to the "random waypoint" model [114]. This defines the nodes' movement scenario files with certain characteristics. The pause times used in each movement scenario file, for each simulation were used from common work. Each node begins a simulation by remaining stationary for a number of seconds equal to the pause time. It then selects a random destination in the defined topology area (the 900m x 300m space) and moves to that destination at a random speed. This random speed is distributed uniformly in (0, Max Speed]. Upon reaching the destination, the node pauses again for a number of seconds equal to the pause time, and then selects another destination, and proceeds there as previously described. This movement pattern is repeated for the duration of the simulation. Each simulation runs for 900 seconds of simulation time.

The movement patterns were generated by Carnegie Mellon University's movement generator [115] (setdest). All simulations were run with movements generated for 7 different pause times: 0, 30, 60, 120, 300, 600, and 900 seconds. A pause time of 0 seconds corresponds to continuous motion, and a pause time of 900 (the length of the simulation) corresponds to no motion.

In the 70 pre-generated scenario files different movement patterns were used, 10 for each value of pause time. All connection methods were run on the same 70 movement patterns. All the simulations were run with the mobile node's mobility at the maximum speed of 1m/s.

### 5.3.4 Communication model

In the simulations, constant bit rate (CBR) sources are used in order to compare the performance of each implementation with routing protocols. UDP is used instead of TCP as the transport layer protocol. These communication models are selected to ensure the packet delivery of the simulations depends only on the routing protocols.

To investigate the different Internet connection methods, communications from MANET to Internet and from Internet to MANET are evaluated. As an extension for point-to-point communication in the MANET, MANET->Internet->MANET communication is also studied.

When choosing the communication model for the MANET to Internet case, the communication patterns were selected with 10 wireless CBR sources and one wired node as destination. By increasing the number of sources from 10, to 20, to 30, simulations for various data transmission rates were taken. When choosing the communication for the Internet to MANET case, the communication patterns were selected with one wired CBR source and 10 wireless nodes as destinations. All the source's transmission rate was 1 packet per second and its packet size was 64 bytes. To have a fair comparison, all communication patterns were started at a time uniformly distributed between 100 and 200 seconds.

All the simulations are run 10 times and the results shown in the figures are the average. There may be some unexpected oscillations in the results. So ideally, the run-time should be continued until no changes in the average results are found.

### 5.3.5 Metric of Comparison

Several metrics are compared between all the connection methods. They are packet delivery ratio, routing overhead and average packet end-to-end delay time. These metrics are not independent and their results should be cross-examined. For example, lower packet delivery ratio due to high node mobility may mean that only packets using shorter path are delivered, resulting in low delay times. And higher packet delivery ratio due to the low node mobility may result in a high delay time since those packets going through longer route are delivered.

- The packet delivery ratio is the number of packets received / number of packets sent, which means that any packets queued in the network are assumed to be undelivered.
- The routing overhead is defined as the total number of messages transmitted for routing purposes. For *AODV-P*, the routing overhead includes the IG broadcast messages and AODV routing messages. For *AODV*, it contains the AODV routing messages only. The routing

overhead for GAW, *DSDV-S* and *DSDV* includes all the routing table update messages and the IG's broadcast messages.

- The average packet end-to-end delay time is defined as the time a data packet is received by the destination minus the time that it is generated by the sources. It includes all the possible delays such as route discovery, queuing in the interface queue, retransmission delays at the MAC propagation and transfer times. For *AODV-P* and *AODV*, it includes the route discovery time and the packet delivery time. However, for GAW, *DSDV-S* and *DSDV*, it is only the packet delivery time.

## 5.4 Simulations from MANET to Internet

### 5.4.1 Overview

In this section of the thesis, simulation results for MANET to Internet communication are introduced. All the simulations have been carried out using the same general simulation setup described in section 5.3. The results will be shown in two parts.

In the first part, section 5.4.2, as the proactive gateway discovery method is used in *AODV-P*, *DSDV-S*, *DSDV* and GAW, the results show the performance of each implementation when the IG's broadcast interval varies from 0 to 60 seconds. The individual results for packet delivery ratio and routing overhead are given. Apart from the IG's broadcast interval, the influence of the mobility of mobile nodes are shown as well. The same scenarios have been carried out using node mobilities of 0, 60, 300 and 900 seconds and more detailed analysis of this is given in part two.

In the second part, section 5.4.3, in-depth performance analysis is presented for all the connection methods with 10 data sources when the IG's broadcast interval is fixed at 10 seconds and node mobilities vary from 0 to 900 seconds. The results of three different IG's locations are shown, one at (0,0) one at (200,100) and one (450,150). By increasing the number of data sources from 10 to 30, the effects of increasing traffic loads have been analysed. Finally, the routing efficiency and the load-balancing scheme of the GAW routing method are shown with the route distribution comparisons between each implementation in section 5.4.4.

A conclusion on the overall performance is given in section 5.4.5 to summarise the results for all MANET to Internet simulations.

### 5.4.2 Performance vs. IG Broadcast Interval

*A. Simulation Setup*

In the implementations, *AODV-P*, *DSDV-S*, *DSDV* and GAW use the proactive gateway discovery method. In this part of the simulation, the IG broadcast interval for them has been set up by a timer varying from 0 to 60 seconds. All the protocols have been run against the same pre-generated scenario files. The simulations use the general set up and other parameters shown in Table 5.5.

*Table 5.5 Parameters for MANET to Internet Simulation when the IG's Broadcast Interval Varies*

| Parameter | Value |
|---|---|
| Protocols | AODV-P, DSDV, GAW |
| Source(s) | 10 Wireless Nodes |
| Destination(s) | 1 Wired Node |
| Number of Wired Nodes | 3 |
| IG Position | (0,0) |
| IG Broadcast Interval | 5 to 60 Seconds |

### *B. Results for AODV-P*

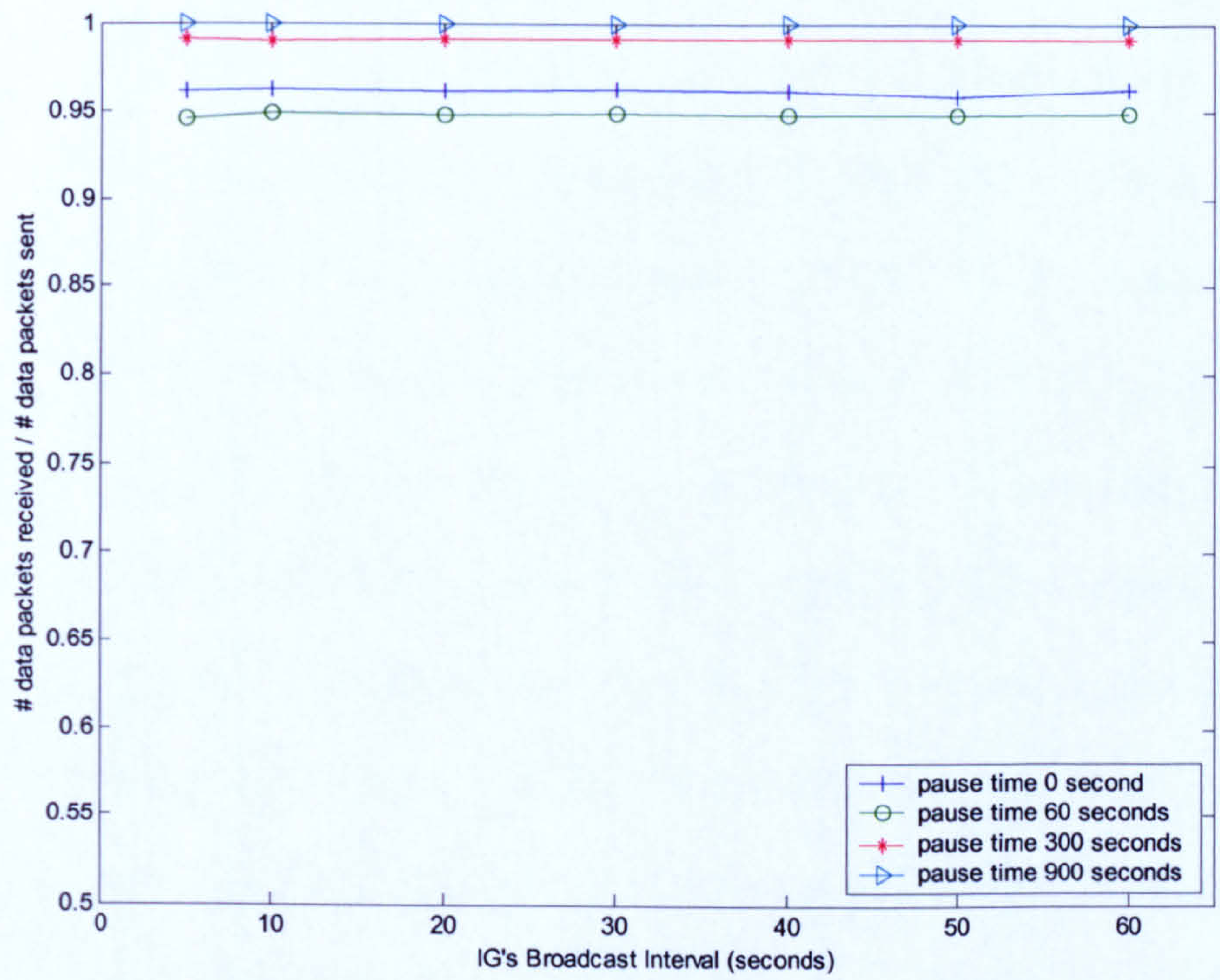



*Figure 5.4 Packet delivery ratio of AODV-P vs. IG's broadcast interval*

As the results show in Figure 5.4, the packet delivery ratio of *AODV-P* remains approximately constant as the IGs' broadcast interval increased. The implementation of *AODV-P* does not have the mechanism for an IG to cancel its duty after sending out the broadcast message. Therefore, in these simulations, once the IG's information has been stored in the wireless nodes' routing tables, it is always available to use and can be restored by the AODV routing protocol when the current link is broken. *AODV-P* queued the packets to the unknown IG and used RREQ_I to search it, so the data delivery ratio is high through route restoration. Consider the node's mobility, the higher node mobility results in a lower data delivery ratio, as broken links happens more frequency than in the case of lower node's mobility. However they all have a constant trend as the broadcast interval varies.

Figure 5.5 shows the routing overhead of *AODV-P*. It decreases as the IG's broadcast interval is increased. The overhead of *AODV-P* comes from the IG's broadcast and AODV route update messages. Clearly, the broadcast causes a heavy overhead when the IG's broadcast interval is small, as the packets flood the whole wireless network. However, considering the constant packet delivery ratio that it has, longer IG broadcast intervals will decrease the routing overhead without losing the delivery ability. The effects of overheads from the AODV update message are shown with the differences when the node's mobility changes. Broken links in the higher mobility case cause more AODV overhead for the route restorations. The decreasing trend of overhead changes against the IG's broadcast interval is not affected by the node's mobility.

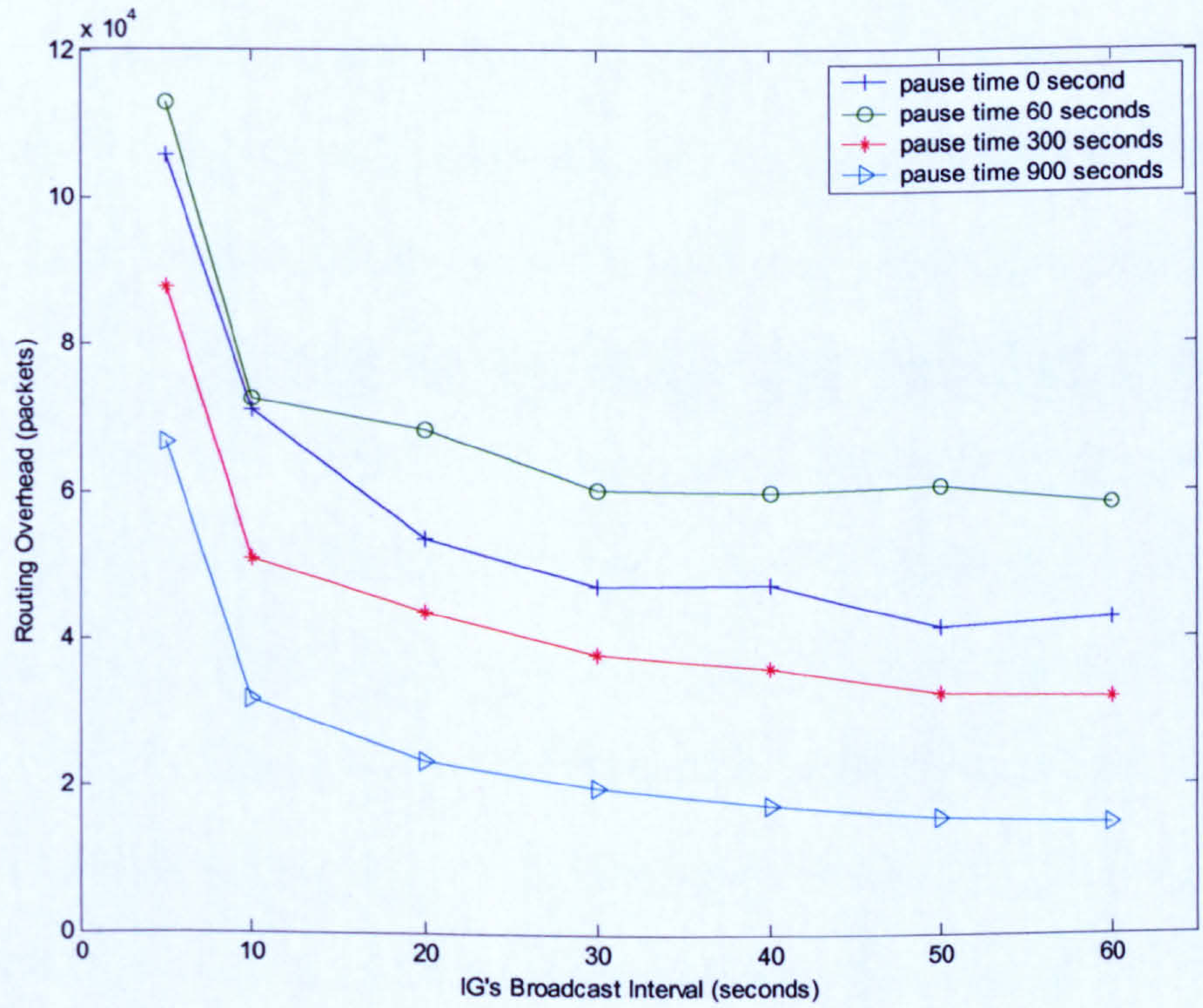



*Figure 5.5 Routing Overhead of AODV-P vs. IG's broadcast interval*

### C. Results for DSDV and DSDV-S

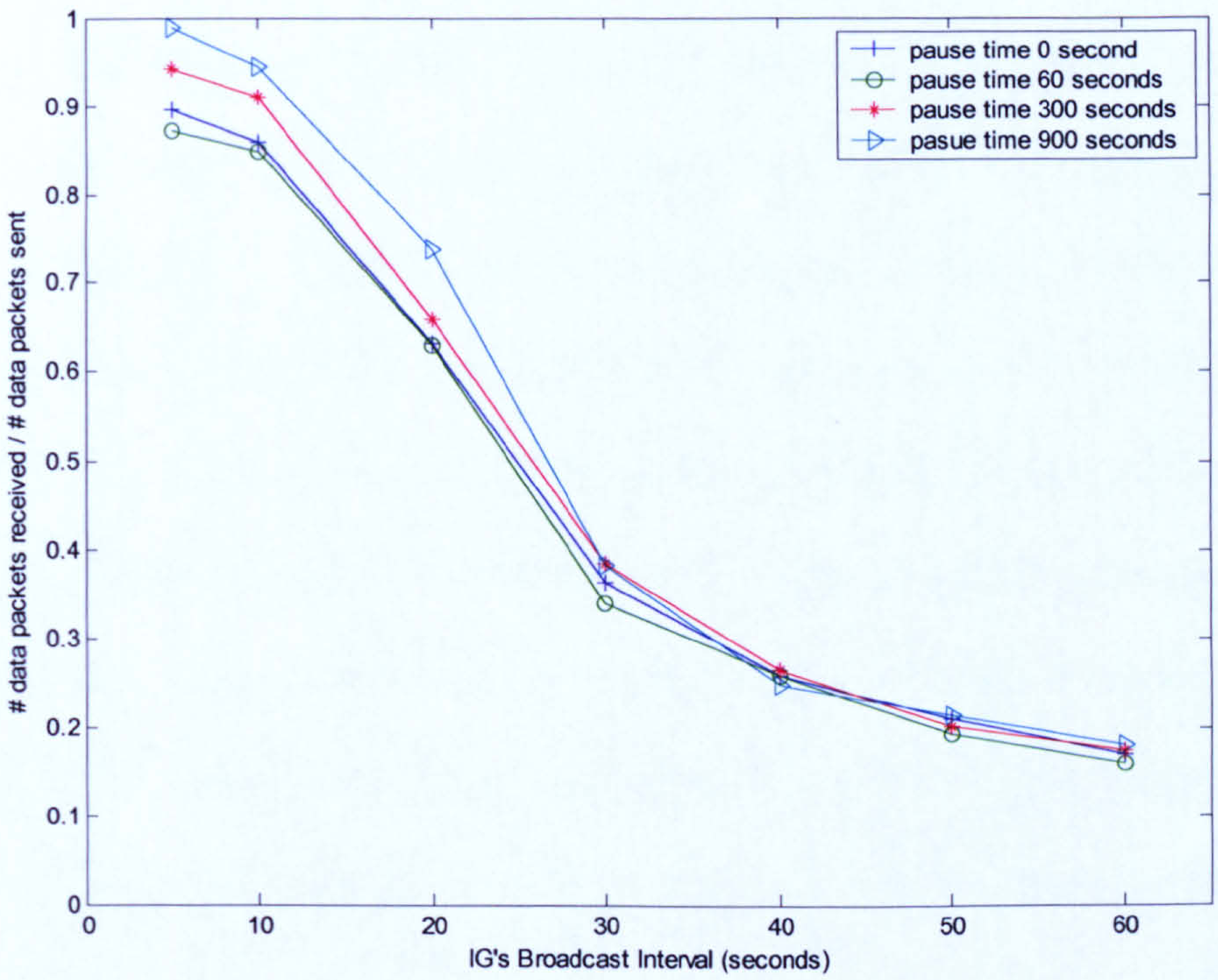



*Figure 5.6 Packet delivery ratio of DSDV vs. IG's broadcast interval*

Figure 5.6 shows the packet delivery ratio for *DSDV*. Given that the IG's route update depends mainly on its broadcast messages, the packet delivery ratio drops significantly when the broadcast interval increases. From Figure 5.6, when the interval is longer than 10 seconds, the packet delivery ratios fall dramatically. The reason is that the *DSDV* update period from the DSDV routing protocol is set to be 15 seconds. When the broadcast interval is longer than 15 seconds, it fails to keep up with the update process, which updates the majority of the route information. Furthermore, the delivery ratio for different node mobilities falls with a negligible difference, which shows that the IG's interval plays a more important role than the node's mobility. However, the broadcast interval is not the only reason for packet dropping. *DSDV*'s route update scheme makes a very slow response to network changes, which means broken links are not quickly detected and may result in packet dropping.

The routing overhead of *DSDV* is shown in Figure 5.7. The *DSDV* periodical updates messages are the majority of the overhead as 30 nodes each generate a periodic update every 15 seconds. To minimise the effect from IG's broadcast messages, the implementation of *DSDV* only adds the IG as one of the wireless nodes. When the IG is added, the IG's broadcast messages slightly increases the overall overhead compared with those from periodical update messages. As a result, when the broadcast interval is decreased, the overhead decreases but not significantly. The overhead from broken links shows in the higher node mobility case with slightly more overhead than the lower ones but not dramatically so.

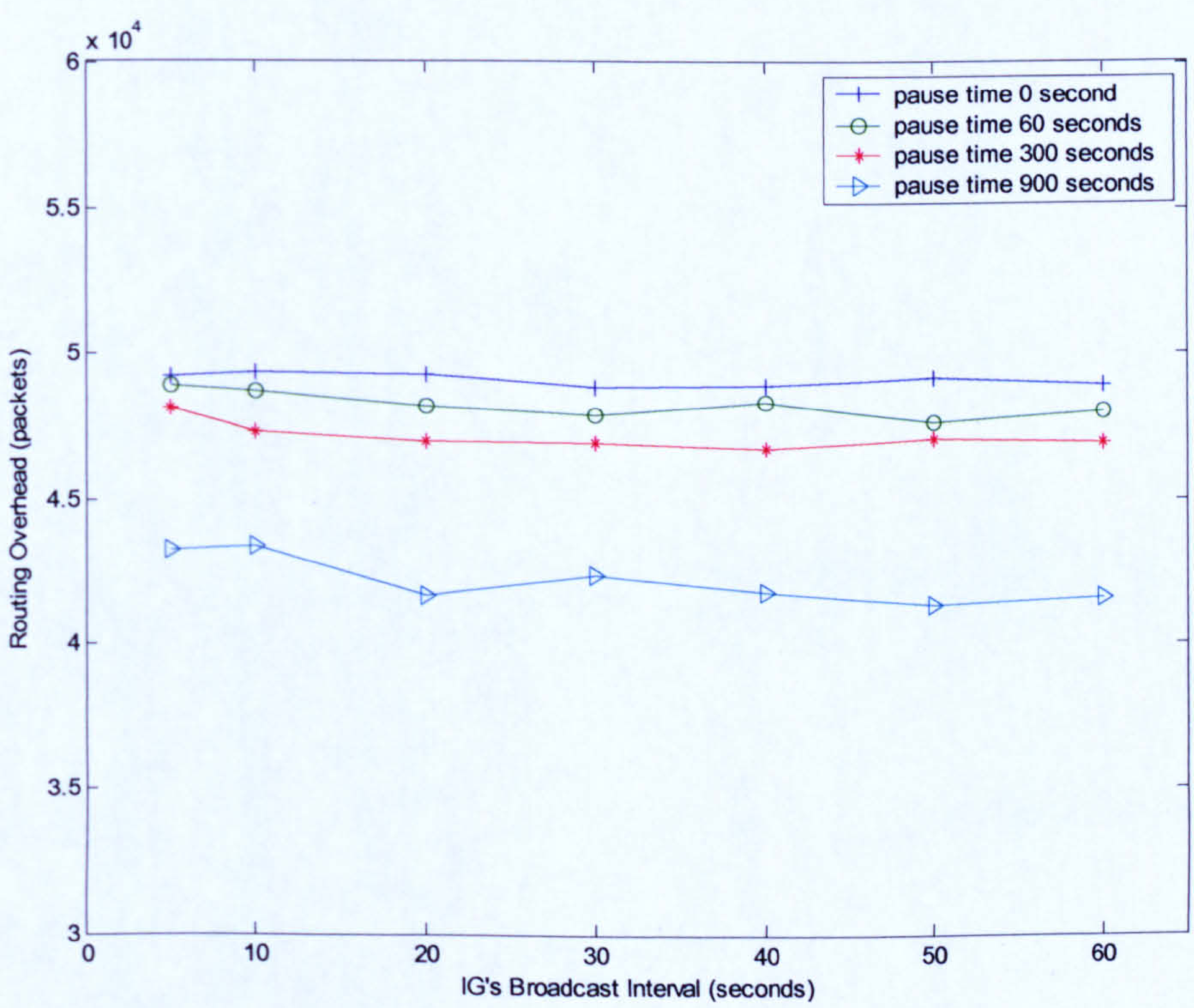



*Figure 5.7 Routing overhead of DSDV vs. IG's broadcast interval*

The results of *DSDV-S* are shown in Figure 5.8 and 5.9. Clearly, although huge overheads are paid by sending out triggered update for every new sequence number, *DSDV-S* also failed to maintain the packet delivery ratio. Since *DSDV-S* has minimised the delay for any network topology changes, it is necessary to find a better gateway discovery to improve the MANET to Internet connection. Noting that due to limited run-time, the simulation results for *DSDV-S* show some unexpected trend. However, these oscillations in the results are most likely to be attributable to a relatively too short a simulation time.

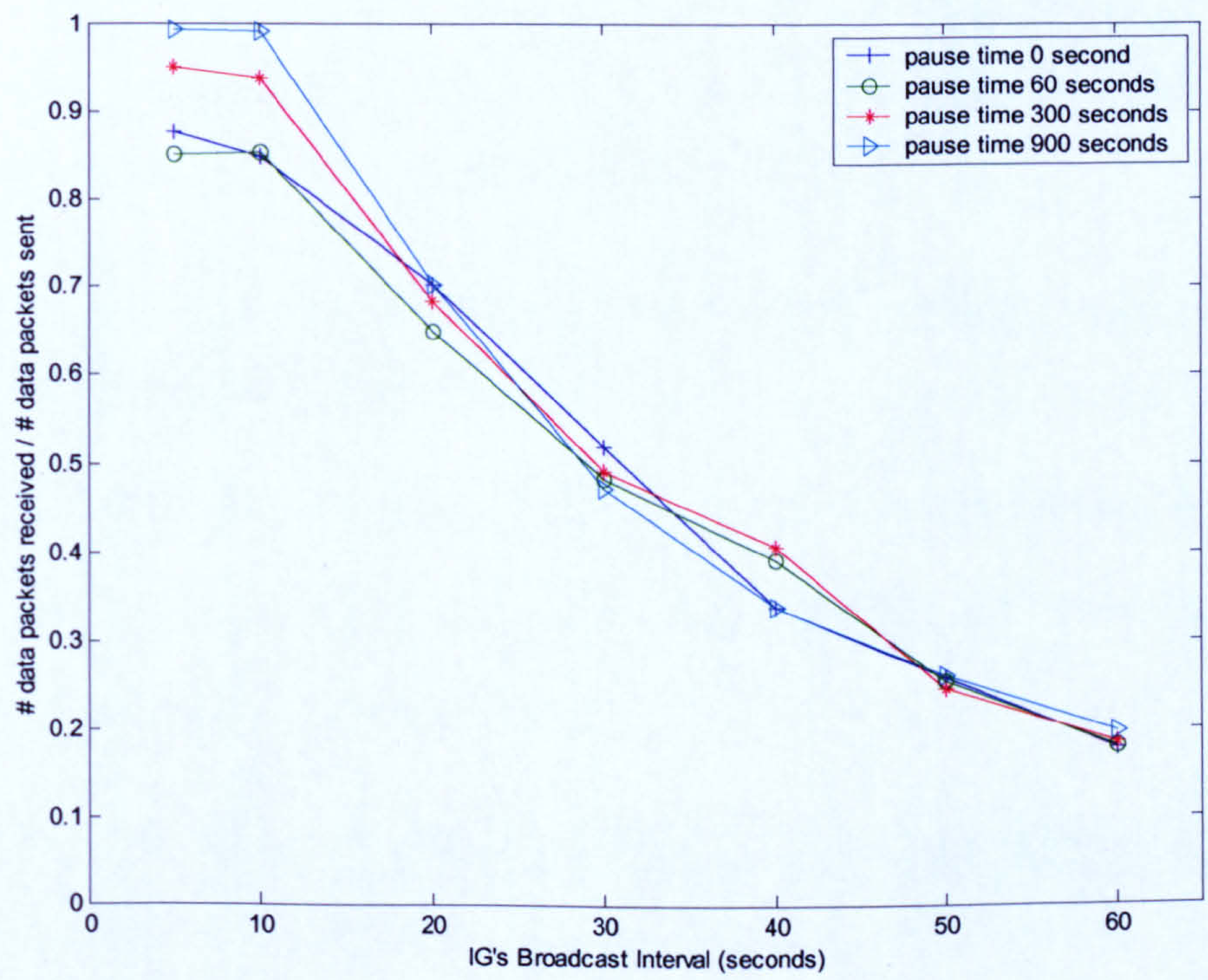



*Figure 5.8 Packet delivery ratio of DSDV-S vs. IG's broadcast interval*

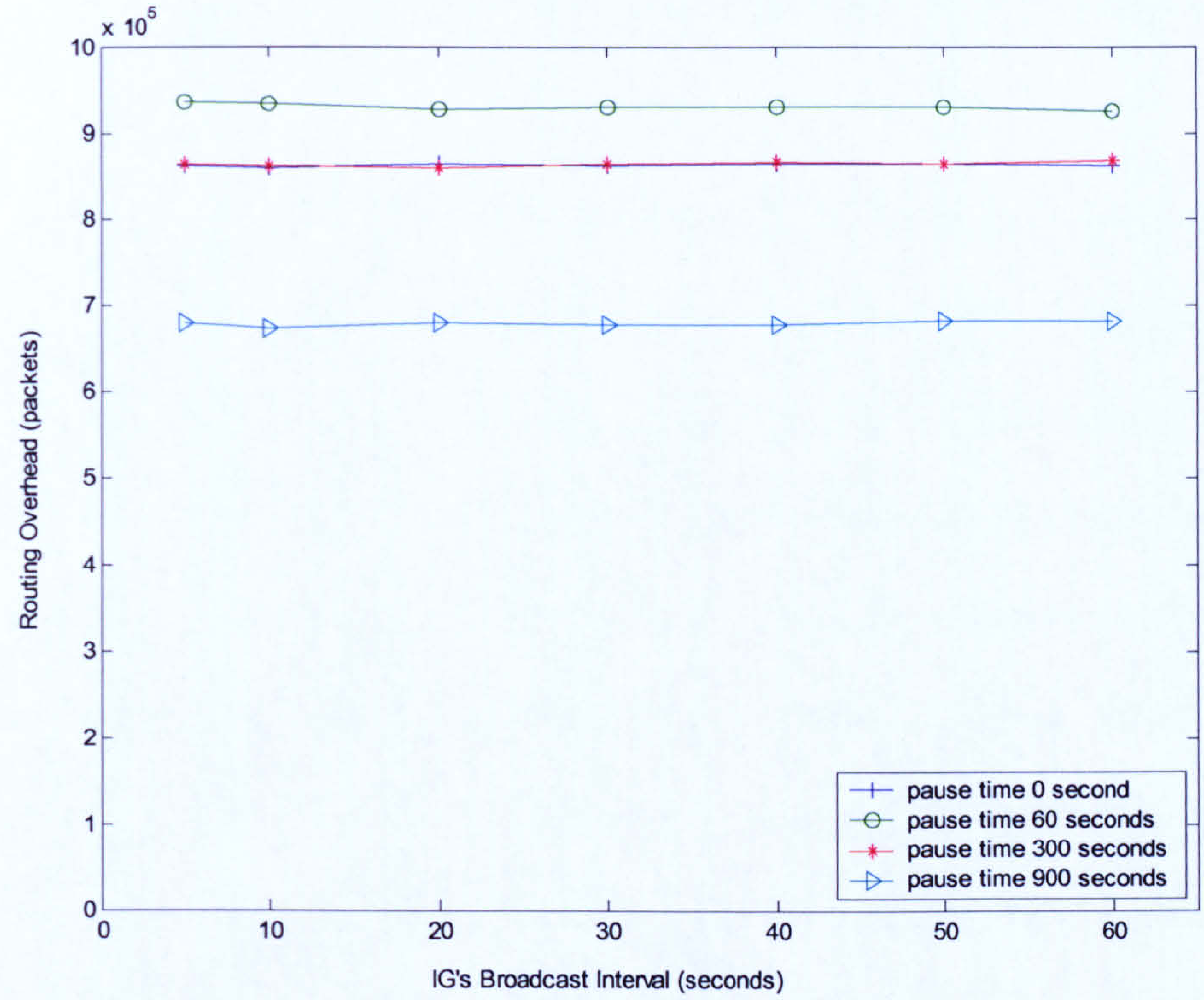



*Figure 5.9 Routing overhead of DSDV-S vs. IG's broadcast interval*

### *D. Results for GAW Routing Method*

The GAW routing method has a different gateway discovery method. An expiry timer for IG is set to improve the Internet connection and GAW states are used to reduce the unnecessary update messages.

First of all, since the GAW state is decided by the timer set for IG expiration, the GAW routing performs a little different when the timer varies. One setting that can be used is that the timer is fixed to be the same as the routing table update period. In this case the GAWNs' state changes do not represent the actual situation changes of the GAWNs. For example, if the IG's broadcast interval is longer than the timer, the GAWN state changes happen earlier (before the changes have been informed). In contrast, if the IG's broadcast interval is less than the GAW state timer, the state changes are out of date compared with the real network situation. Another timer setting option is to set it equal to the IG's broadcast interval, this should result in the GAW state changes representing the real situation.

Figures 5.10 and 5.11 compare the performance of these two timer selections when node mobility is 30 seconds. The results show that with the timer equal to the IG's broadcast interval, the packet delivery ratio is more stable while the other setting failed to deliver and drop significant number of packets. Also when the timer equals the periodical update period, since more unnecessary GAW state change messages were generated, the routing overhead is slightly higher after the IG's broadcast interval over 20 seconds. The reason for the increasing overhead trend in Figure 5.11 is that the periodical update interval of the GAW routing method is 15 seconds. After the IG's broadcast over 20 seconds, the GAW state change messages for all GAWNs will be sent out between a 0 – 15 seconds interval. Again the oscillation in the results is due to the limited simulation times.

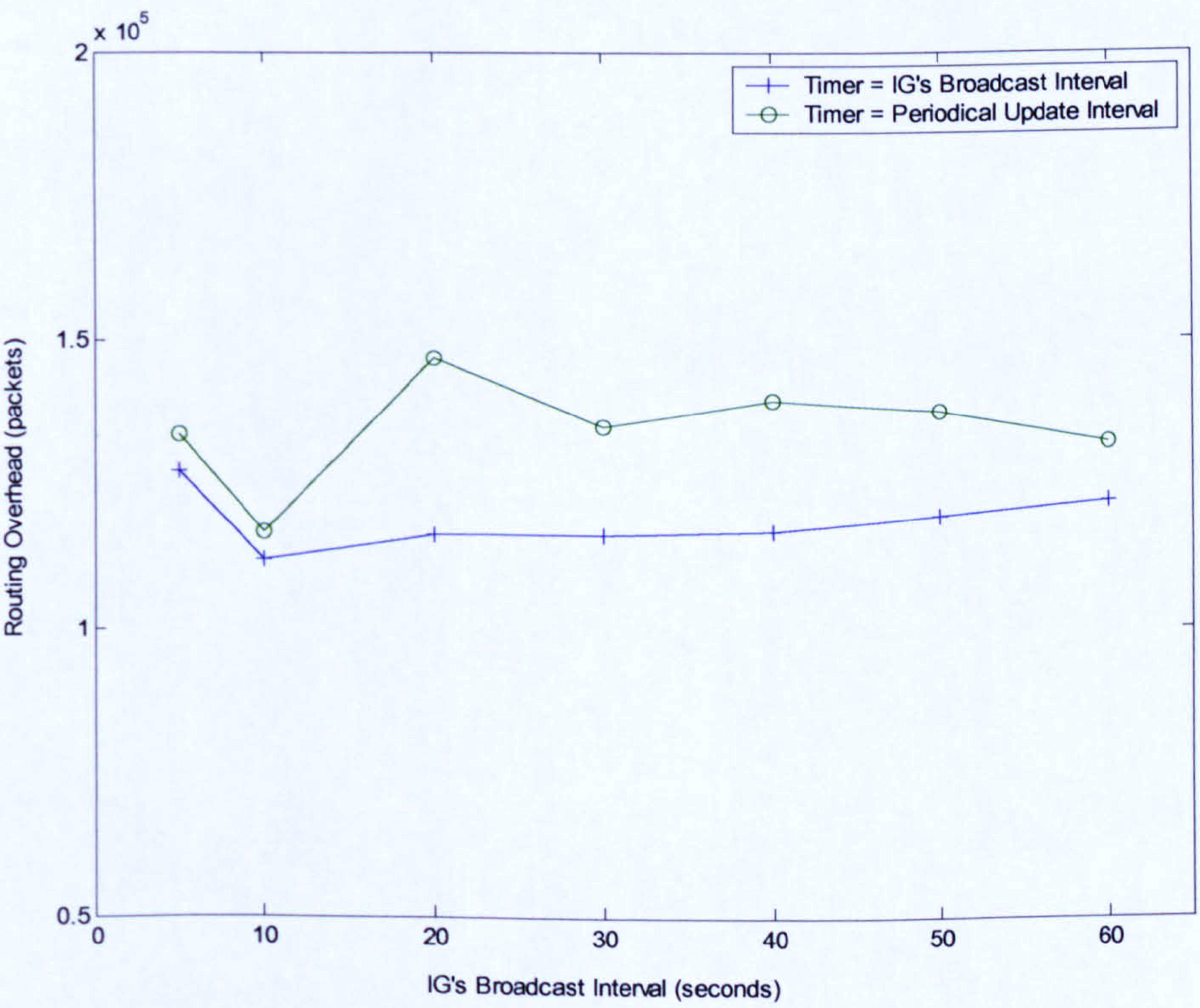



*Figure 5.11 Comparison of Routing Overhead for various GAW Timer*

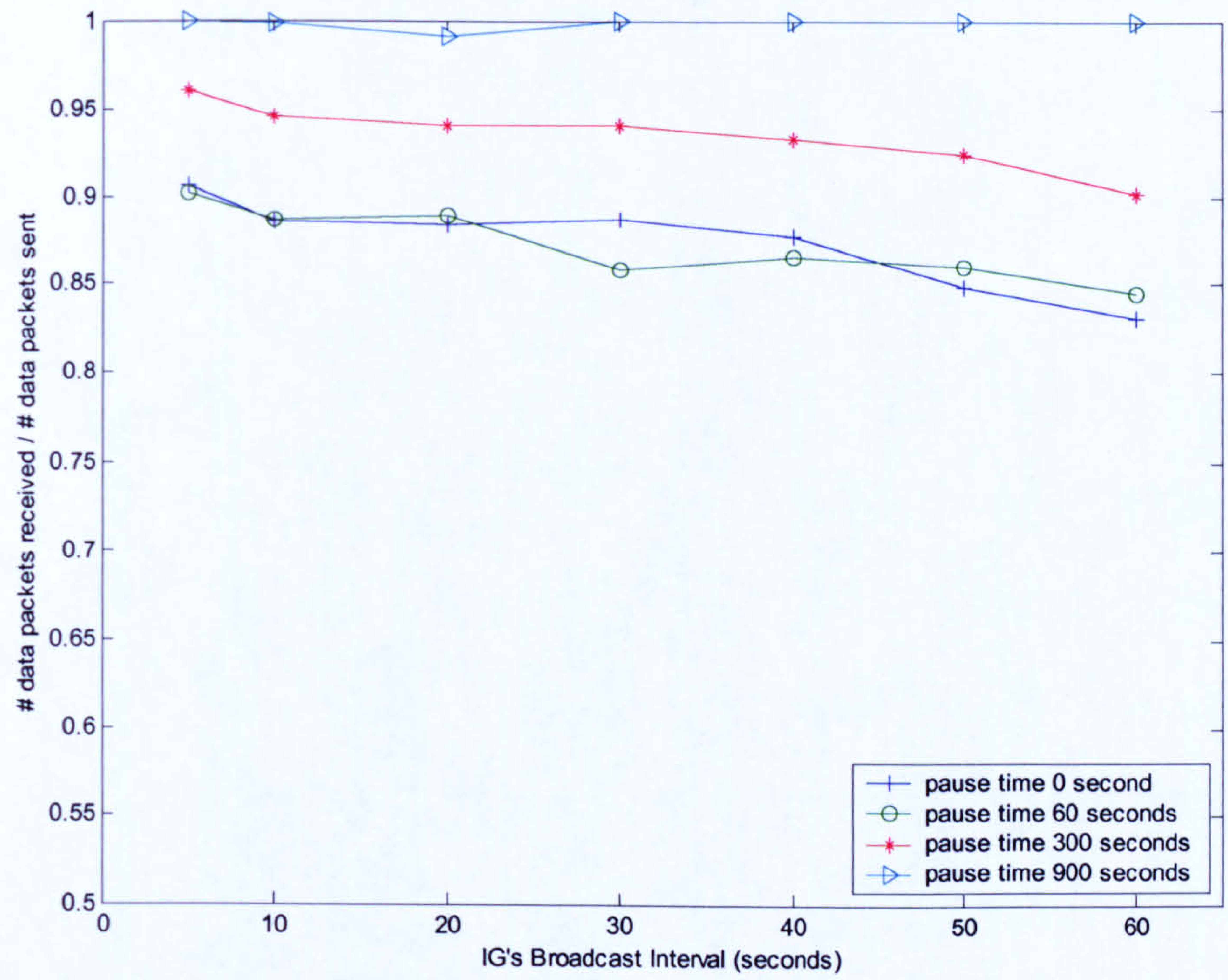



*Figure 5.12 Packet delivery ratio of GAW vs. IG's broadcast interval*

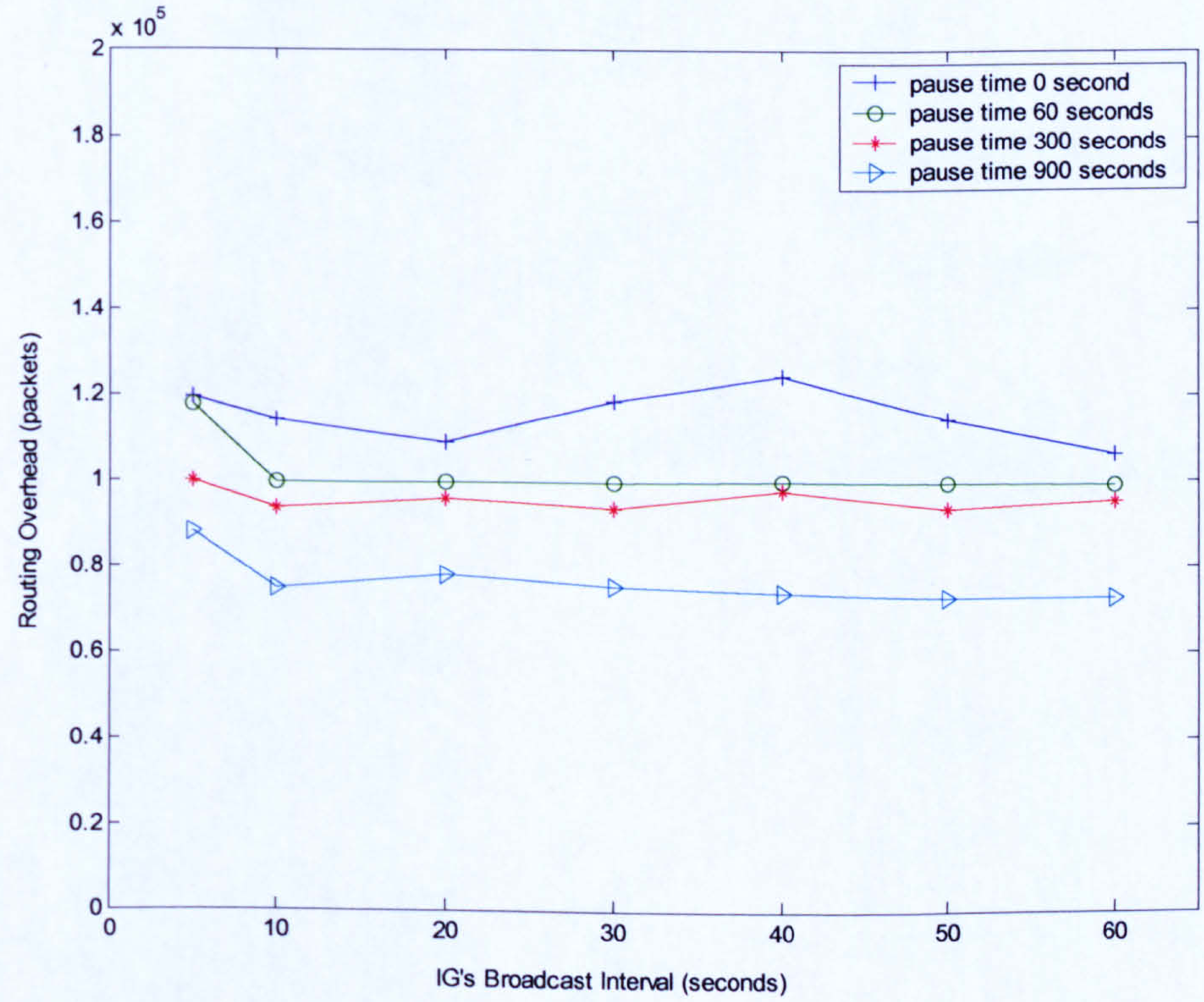



*Figure 5.13 Routing overhead of GAW vs. IG's broadcast interval*

In the following simulation work from this point, the IG expiry timer is set to the IG broadcast period. This setting ensures that the GAW state indicates the actual GAWN situation. As shown in Figure 5.12, GAW generally offers nearly a constant delivery ratio and drops slightly when the IG broadcast interval is longer. Unlike DSDV, no matter how long the IG broadcast period is, GAW achieves a good delivery ratio. Apart from the chosen of expiry time, the other reason is that although the GAW routing method uses the same periodical update timer as DSDV (at 15 seconds), it updates the routes to GAWNs more frequently with the GAW state changes being immediately sent out with trigger update messages. So, the links to GAWNs are therefore well maintained. The layer of GAWNs also provides alternative routes when one GAWN has lost the connection. However, the GAW routing method uses the proactive route update method, so the packets decrease a little when the IG's broadcast interval increases. This method brings extra overhead to the network as shown in Figure 5.13. As the majority of the overhead arises from the periodical update messages, the overhead of GAW appears to be constant. The results also show that lower mobility does result in higher delivery ratio whilst the routing overhead is constant.

### 5.4.3 Overall Performance

*A. Simulation Setup*

To compare the performance with AODV using the reactive gateway discovery method, simulations have been carried out with a fixed IG broadcast period of 10 seconds. The choice of 10 seconds is based on the performance in section 5.3.2 and the default periodical update timer of GAW, *DSDV-S* and *DSDV*. From the results in section 5.3.2, *DSDV* performed worst when the IG broadcast interval was more than 10 seconds. Since GAW and *DSDV* also have the periodical update timer set at 15 second. The choice of 10 seconds would be close enough to the periodical update message from the IG and should not affect the overall performance of proactive gateway discovery methods.

*Table 5.6 Parameters of Overall Performance Comparison Simulation for MANET to Internet*

| Parameter | Value |
|---|---|
| Protocols | AODV-P, AODV, DSDV-S, DSDV, GAW |
| Source(s) | 10, 20, 30 Wireless Nodes |
| Destination(s) | 1 Wired Node |
| Number of Wired Nodes | 3 |
| IG Position | (0,0) (200,100) (450,150) |
| IG Broadcast Interval | 10 Seconds |

The locations of the IG have been chosen from the far end to the middle of network topology in order to investigate the effect of IG locations on the performance of connection methods. All implemented routing protocols and gateway discovery methods have been simulated with the 70 scenario files. The simulation parameters are shown in Table 5.6.

The routing efficiency and load-balancing scheme of GAW is also investigated using 10 data sources in the scenario with 900 seconds pause time. The choice of no node mobility is made to consider the route selection being done for each packet assuming the network information is unchanged at that time. The zero node mobility scenarios make the route distribution analysis somewhat easier.

***B. Performance comparison with IG at (0,0)***

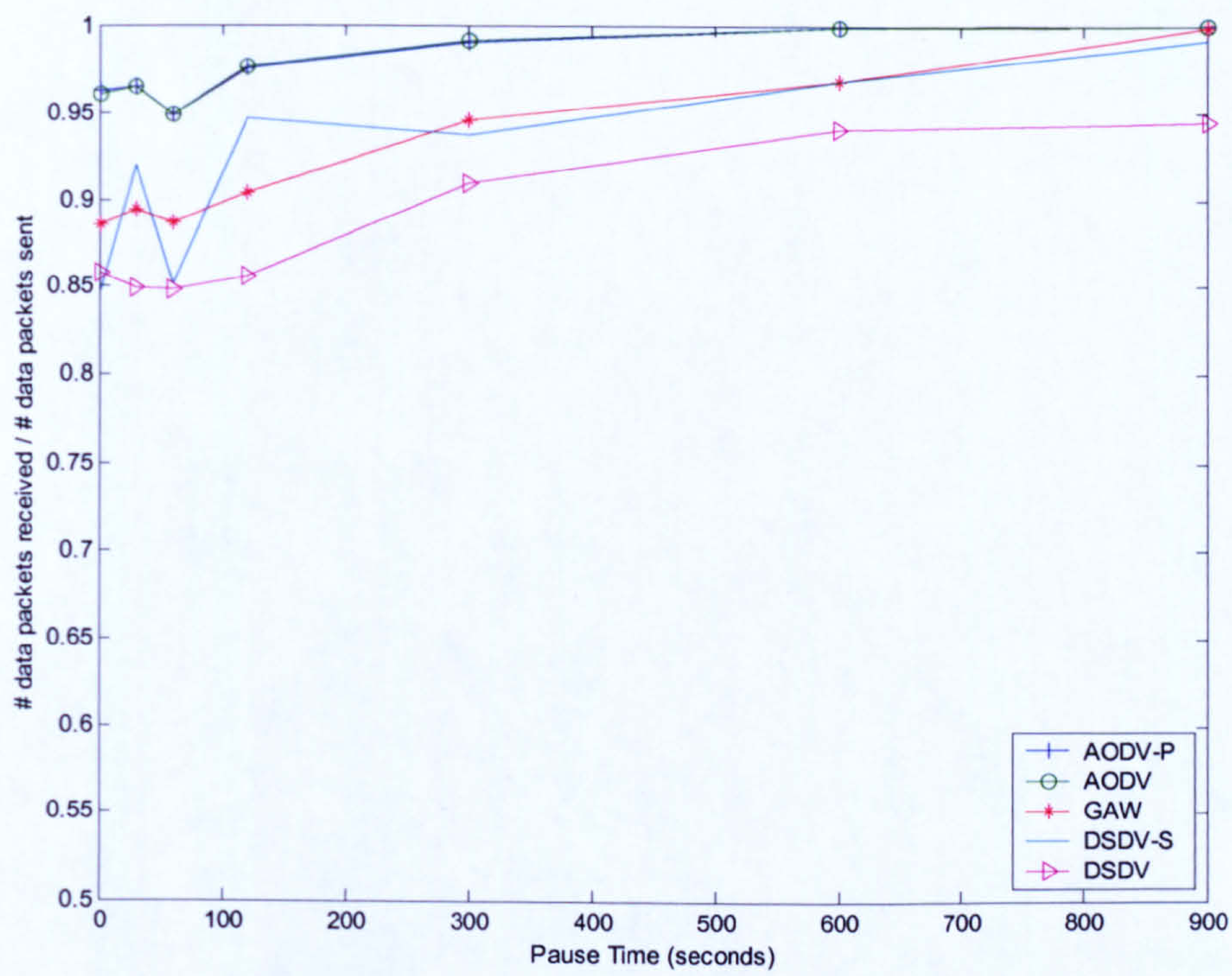



*Figure 5.14 Packet delivery ratio vs. node's mobility for IG at (0,0)*

Figure 5.14 shows the packet delivery ratio of *AODV-P*, *AODV*, GAW, *DSDV-S* and *DSDV* when the nodes' mobilities are increasing from 0 to 900 seconds. As may be expected, the packet delivery ratios for all the protocols tend to be better when the node mobility reduces. With the exception of *DSDV*, all protocols managed to deliver nearly 100% of the packets when the nodes were stationary. Proactive and reactive AODV had more or less the same packet delivery ratios above 95% and perform better than the others. GAW had a delivery ratio above 90%. Since not relating to the IG discovery method, the huge amount of trigger update messages in *DSDV-S* still can not provide stable routing information. So *DSDV-S* acts in a very unstable manner with an above average packet delivery ratio close to that of GAW. *DSDV* had above 85% of packet delivery ratio in this case.

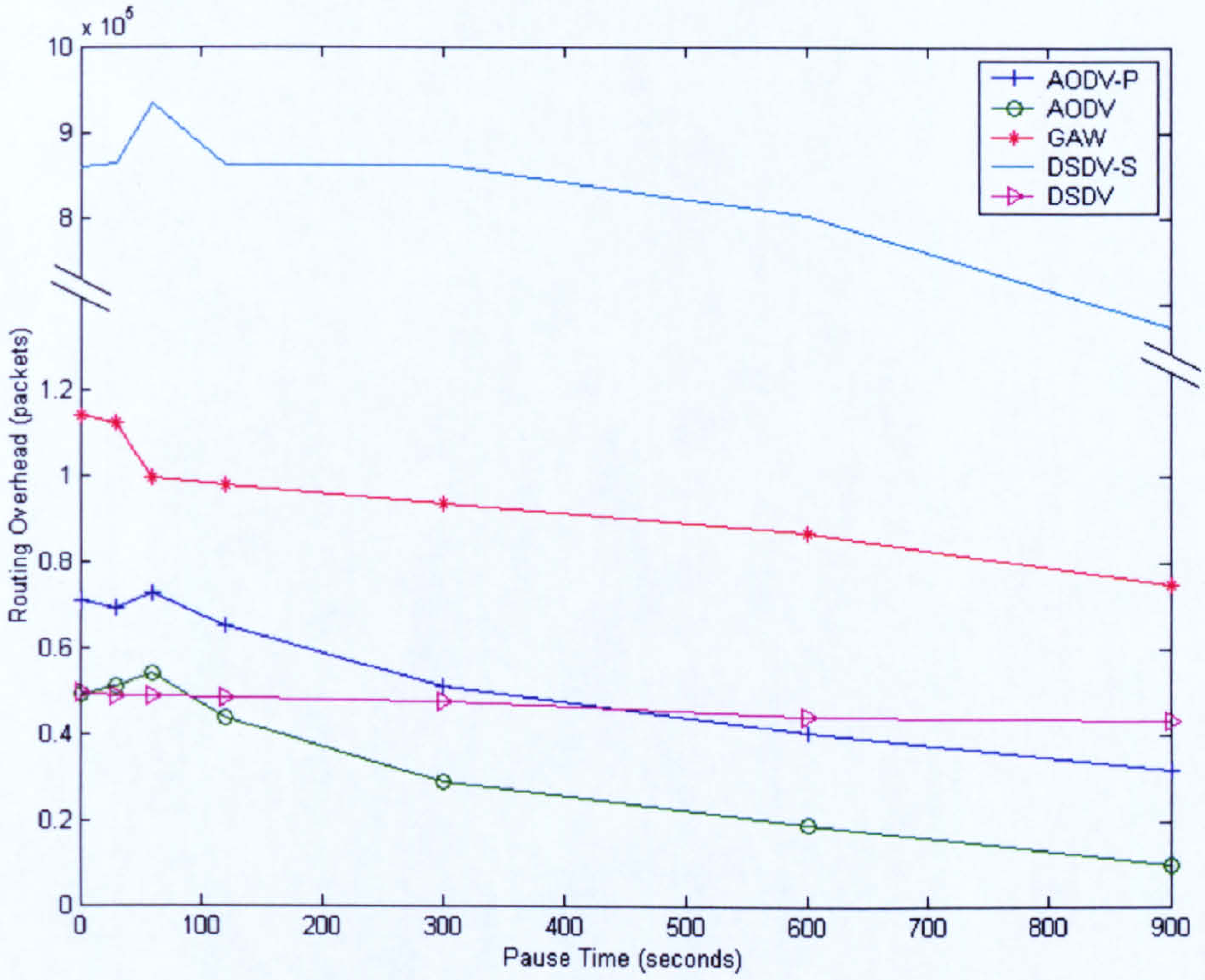



*Figure 5.15 Routing overhead vs. node's mobility for IG at (0,0)*

The routing overhead is shown in Figure 5.15. GAW, *DSDV-S* and *DSDV* use the proactive routing method, so the majority of their overhead comes from the periodical update messages. As the result shows, to achieve better packet delivery ratios, the GAW routing method employed more trigger update messages for GAWNs and thus the overhead is higher than *DSDV*. However, the overhead paid by GAW is very effective when compared with *DSDV-S*, where both of them achieved nearly the same packet delivery ratio but *DSDV-S* flooded the network. *AODV-P* has a more constant extra overhead than the reactive method *AODV* due to the IG broadcast. In all cases, the routing overhead tends to decrease as the node mobility decreases.

***C. Performance comparison with IG at (200,100)***

When the IG is located at (200,100), it is closer to the centre of the simulation topology. Figure 5.16 shows the packet delivery ratio for all the connection methods. All have achieved much better delivery ratio with IG in this position than with it at the far end of the network. Both implementations of AODV achieved nearly 100% delivery ratio. GAW and DSDV-S improved their performances to above 96%. DSDV is still the worst one but has more than 94% of packet delivery ratio. For all the connection methods, the new location means that there could be more routes to the IG and the hops to the IG are generally reduced. As more routes result in more connection availabilities, less hops to the IG also brings down the number of packets dropped due to broken links.

Figure 5.17 shows the routing overhead of each implementation when the IG is at (200,100). When the IG is moved into the simulation network from the far end, the routing overhead of different kinds of implementations appears to be different. *DSDV-S* still remains the highest routing overhead. *AODV-P* and *AODV* appeared to have less routing overhead since the route discovery to the IG become easier. The GAW routing methods increase its routing overhead by having more nodes turn into GAWNs resulting in more GAW update messages. *DSDV* does not change a lot since the IG was used as a wireless node and the routing overhead caused by it did not change much regarding its location.

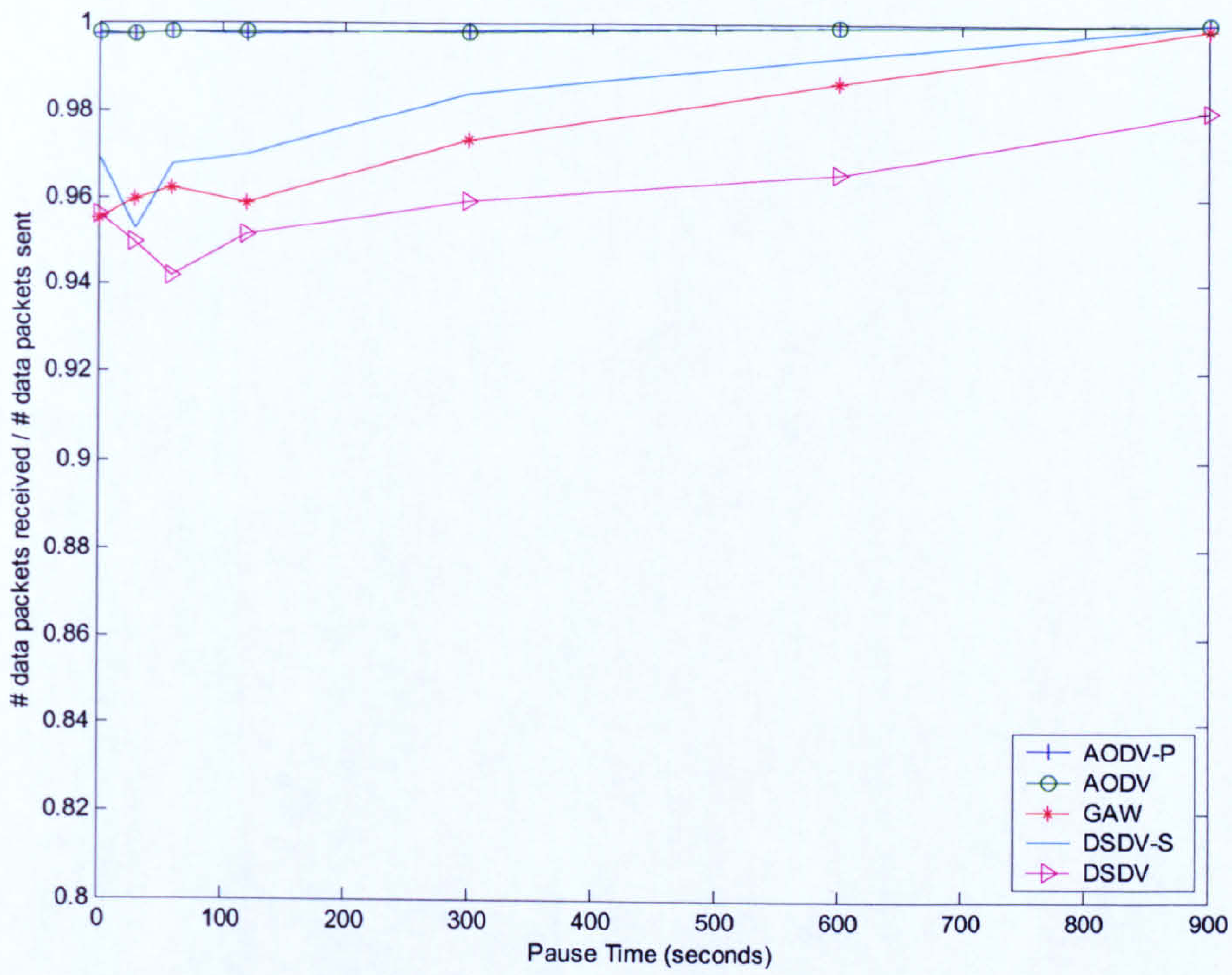



*Figure 5.16 Packet delivery ratio vs. node's mobility for IG at (200,100)*

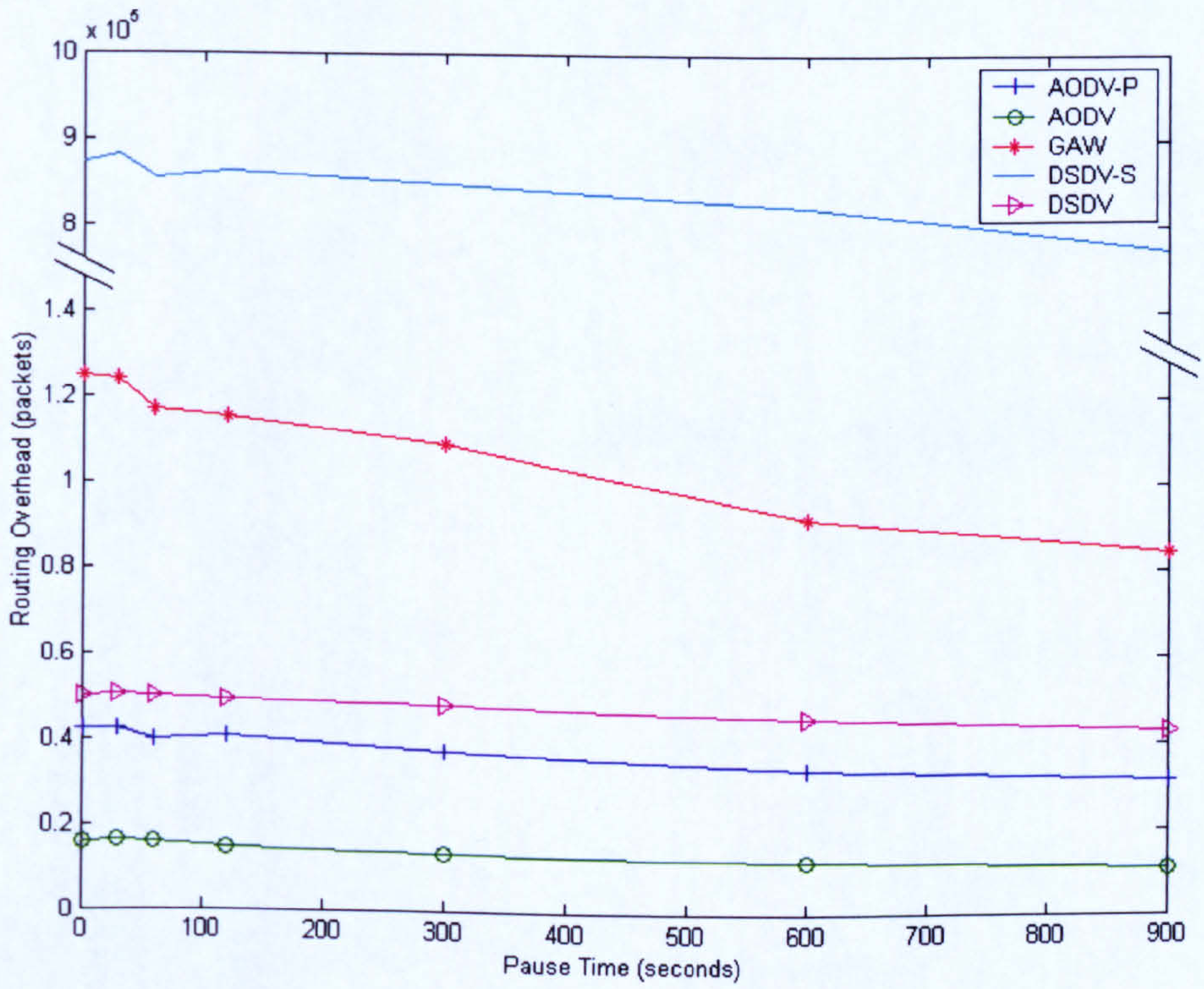



*Figure 5.17 Routing overhead vs. node's mobility for IG at (200,100)*

***C. Performance comparison with IG at (450,150)***

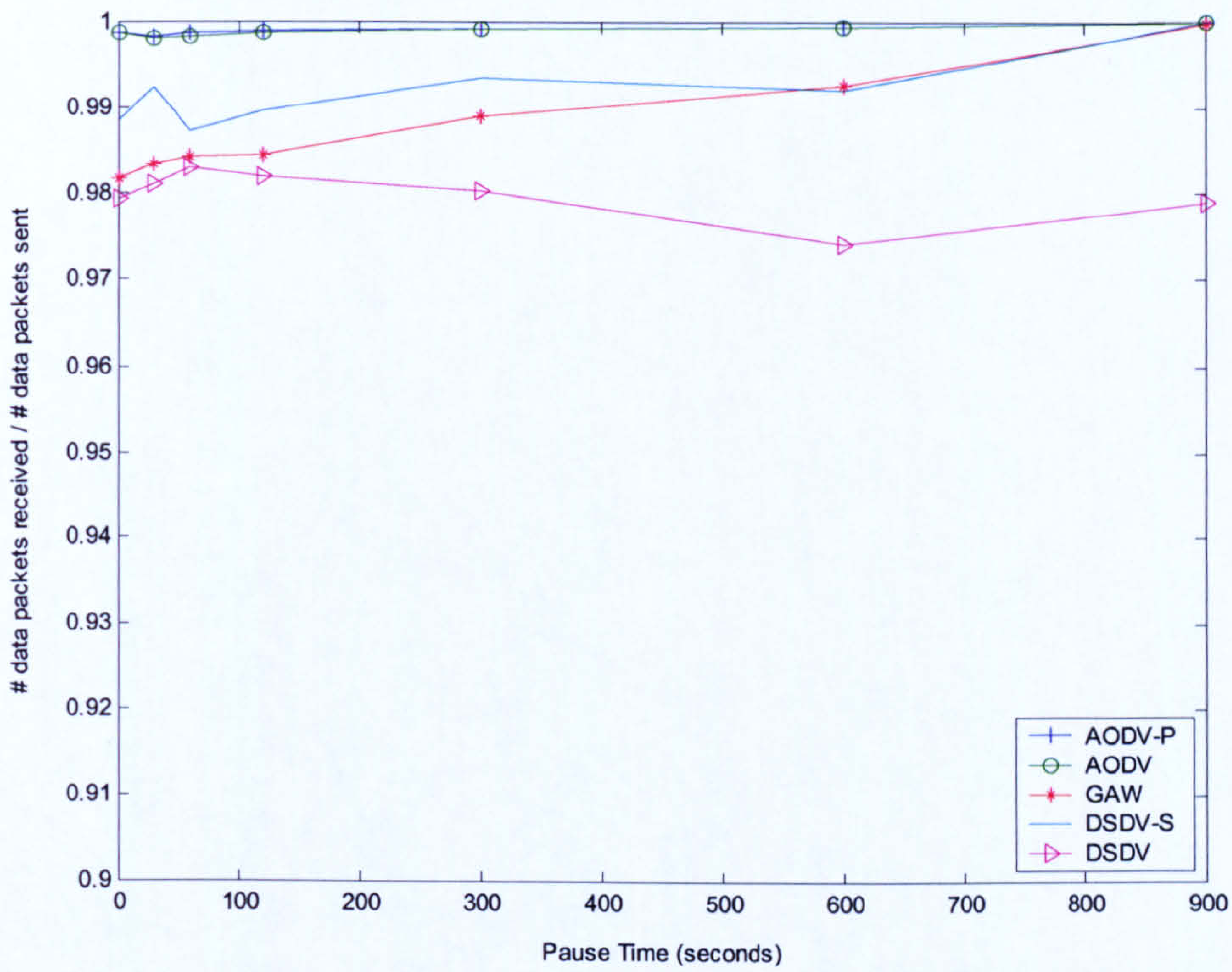



*Figure 5.18 Packet delivery ratio vs. node's mobility for IG at (450,150)*

Figure 5.18 shows the delivery performance of each protocol when the IG is located in the middle of the simulation network. The same trends were shown where all protocols tended to perform better and achieve a delivery ratio above 97%. *AODV-P* and *AODV* have packet delivery ratios above 99% and still perform better than the others. GAW and *DSDV-S* have a delivery ratio above 98%. *DSDV* has above 97% of packet delivery ratio, but was still the only one that failed to deliver 100% when nodes stay stationary.

The packet delivery ratio is much improved with the IG in the centre of network. Considering that the node's density and IG's propagation range is 250m, using *AODV-P*, *AODV* and GAW, a single IG in the middle managed to provide the Internet access service to a rectangular area of 900x300m.

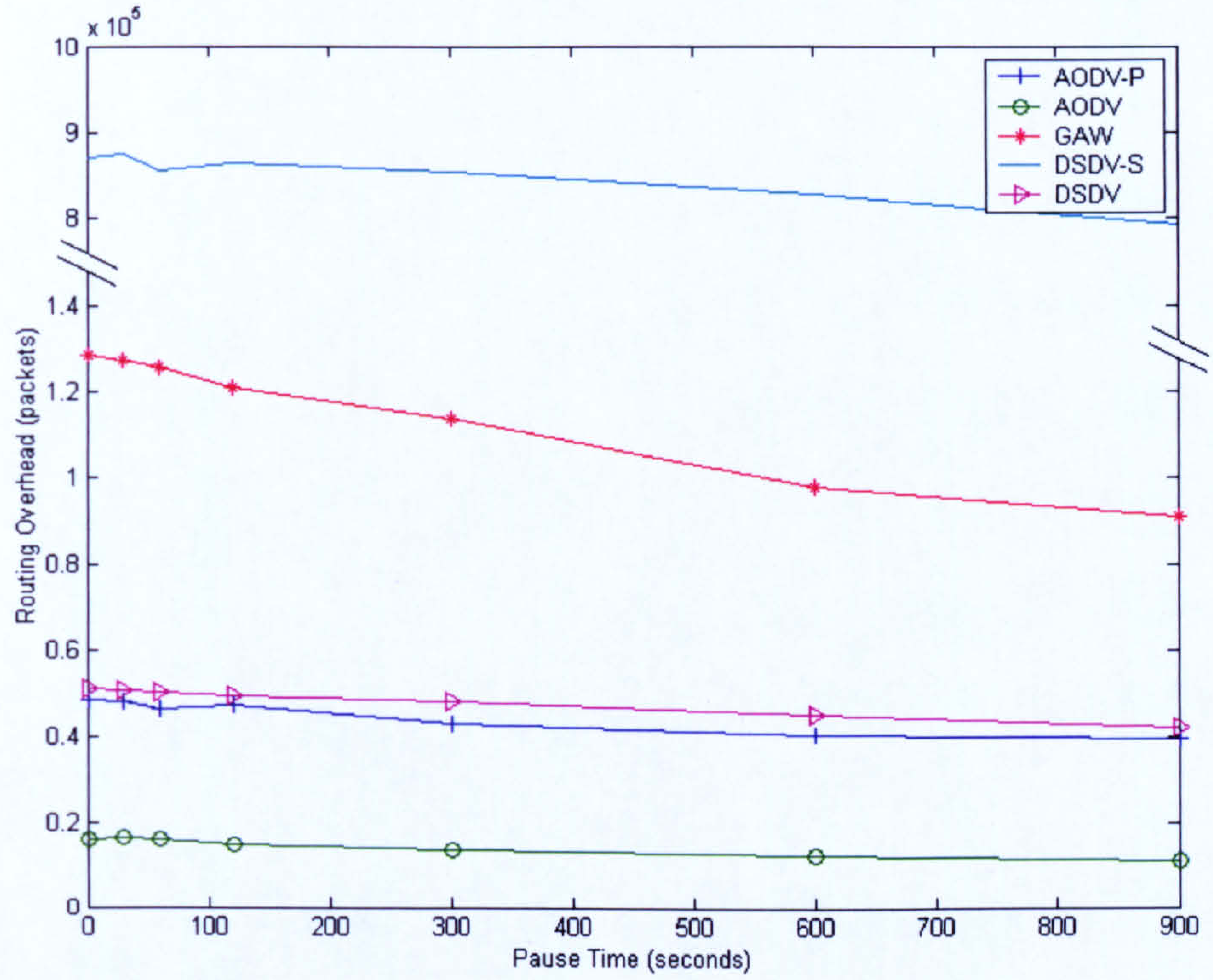



*Figure 5.19 Routing overhead vs. node's mobility for IG at (450,150)*

The routing overhead results are presented in Figure 5.19. Again *DSDV-S* has a huge overhead from the trigger update messages, where it did not achieve the best routing performance. Comparing with the case of the IG at (200,100), the overhead of GAW and *DSDV* did not change significantly. Both *AODV-P* and *AODV* have slightly fewer overheads due to their smaller number of route discovery messages.

***D. Delay Time Analysis***

This section shows the average packet end-to-end delay time using *AODV-P*, *AODV*, GAW and *DSDV*. Figures 5.20, 5.21 and 5.22 show the average end-to-end delay time when the IG is located in the different locations. Generally speaking, the difference between them is that the packets may take longer routes to the destination IG resulting in longer delays. The average hops from destinations to the Internet, which result from the routing efficiency, will be shown in section 5.4.4.

*AODV* with its reactive gateway discovery method must find the routes that are not currently maintained. Although *AODV-P* uses the proactive gateway discovery method, so that the route broadcast by the IG is updated by wireless nodes before it requests a connection to the Internet, it must still search for unknown IGs using the reactive method. Both of them queue packets for unknown destinations so the end-to-end delay time includes both route discovery time and packet delivery time.

GAW and *DSDV* use proactive gateway discovery and route discovery methods, which means they do not queue packets for unknown destinations on the Internet. All the packets delivered are already aware of the route so the delay time is the packet delivery time only.

Figure 5.20 shows the average end-to-end delay time when the IG is at (0,0). The average number of hops from destinations to the Internet was approximately 3. The node's mobility affects *AODV-P* and *AODV* since the route discovery for a longer route (consider the distance to the edge of network) maybe interrupted by the fast changing node position. *AODV-P* obviously spends less time on route discovery than *AODV*, where GAW and *DSDV* have constant and much small delay times. With different route selections to longer routes, GAW exhibited a slightly longer delay than *DSDV* but offered a higher delivery ratio as discussed already.

Figure 5.21 shows the average end-to-end delay time when the IG is at (200,100). When the IG is in this position, the routes to the IG from data sources are shorter, with the average number of hops from destinations to the Internet being around 2. As a result, the node's mobility has a lower effect on the delivery delay time. *AODV* still has longer delays than *AODV-P*, representing the time spent on discovering unknown IG routes. Both GAW and *DSDV* retain low delay times.

Figure 5.22 shows the average delay time when the IG is at (450,150). The average number of hops from destinations to the Internet was roughly 1.5. The delay time in this case is very much like the one when the IG is at (200,100). *AODV-P* has less delay than *AODV* since some routes to the IG are already known from the periodical broadcast. The difference between GAW and *DSDV* is not very clear but both exhibit much shorter delays than *AODV-P* and *AODV*. There are some unexpected trends in the results of *AODV-P* and *AODV*. It is considered that, after sufficient simulations, these trends may be eliminated.

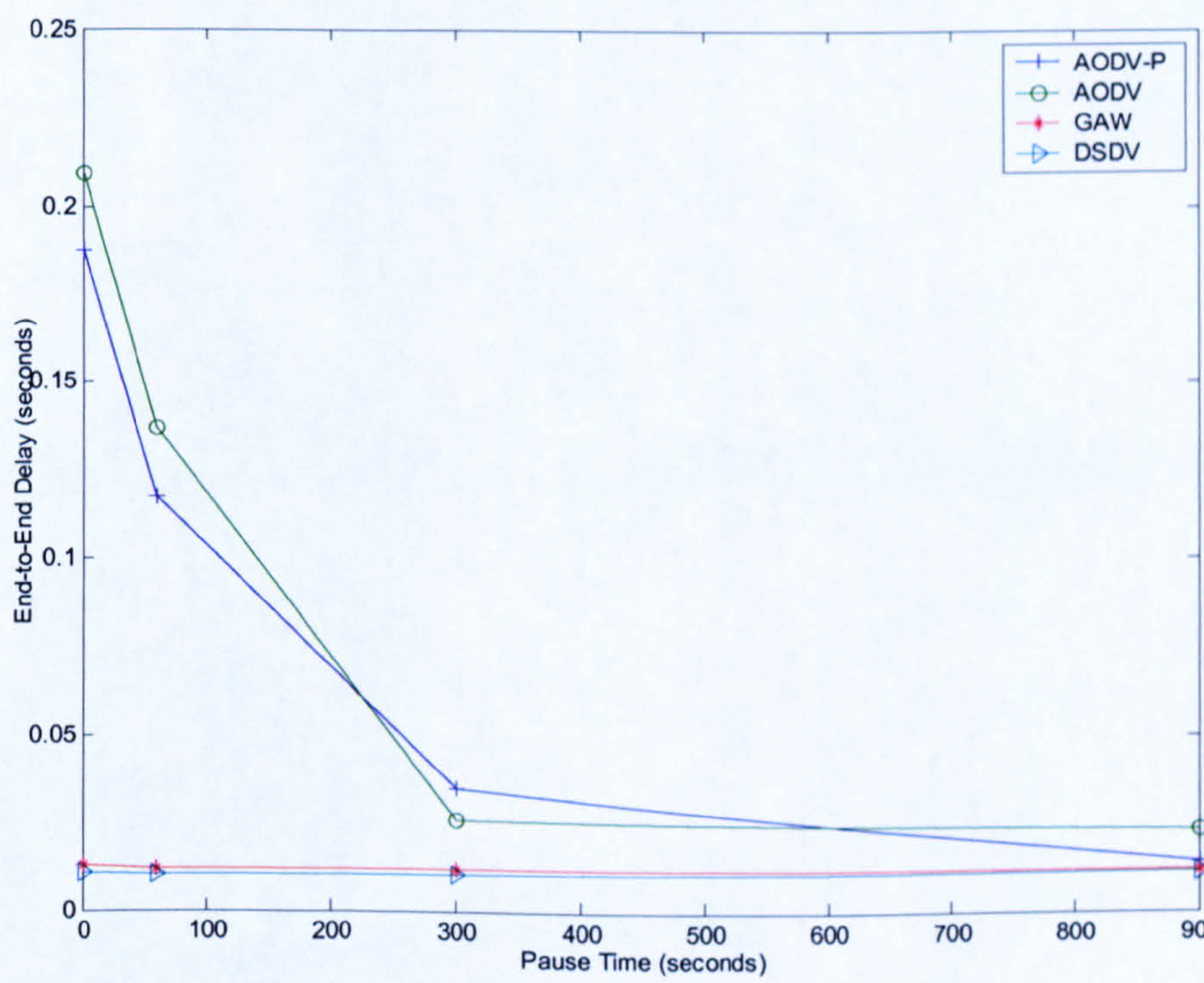



*Figure 5.20 Average End-to-End Delay time vs. node's mobility for IG at (0, 0)*

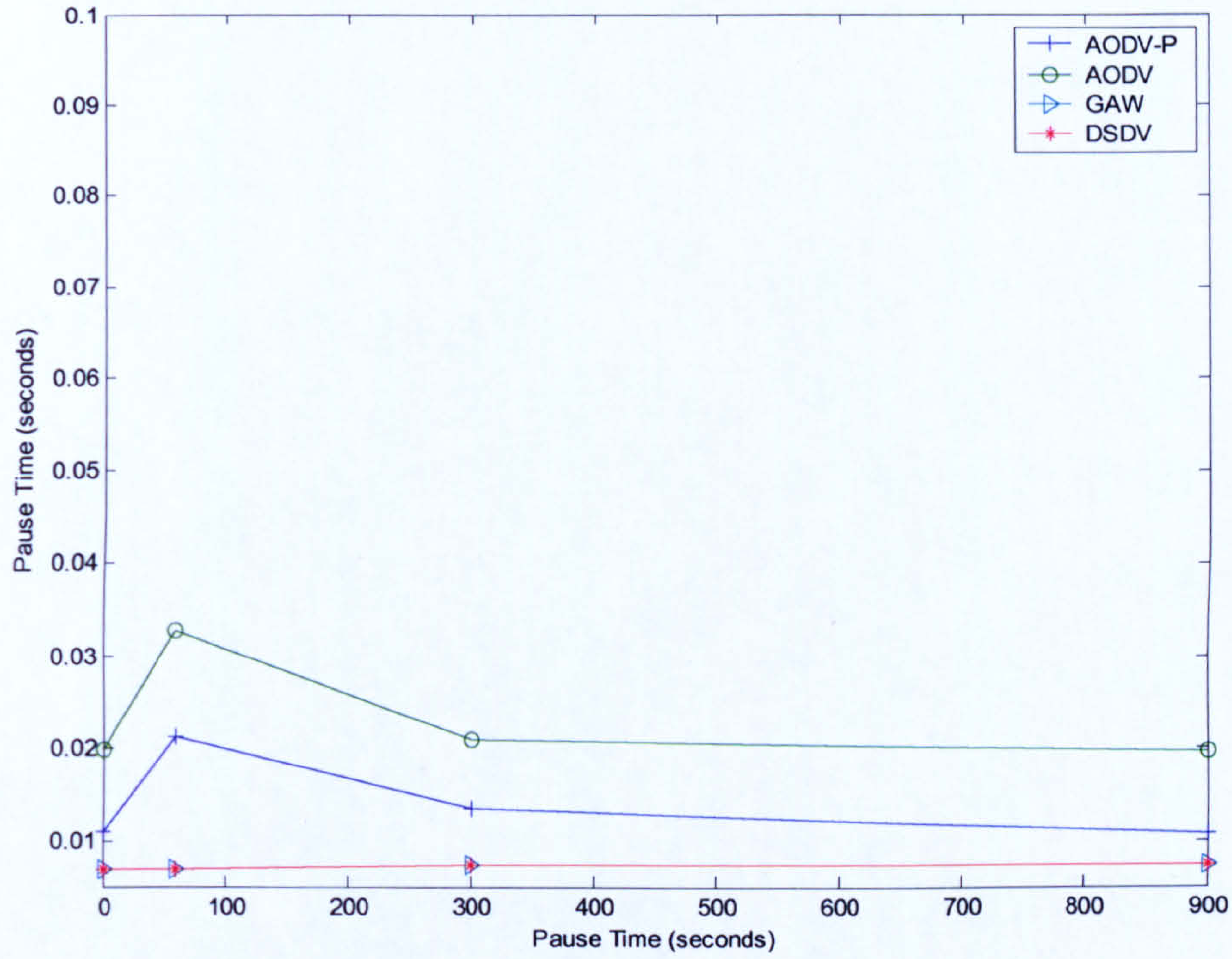



*Figure 5.21 Average End-to-End Delay time vs. node's mobility for IG at (200, 100)*

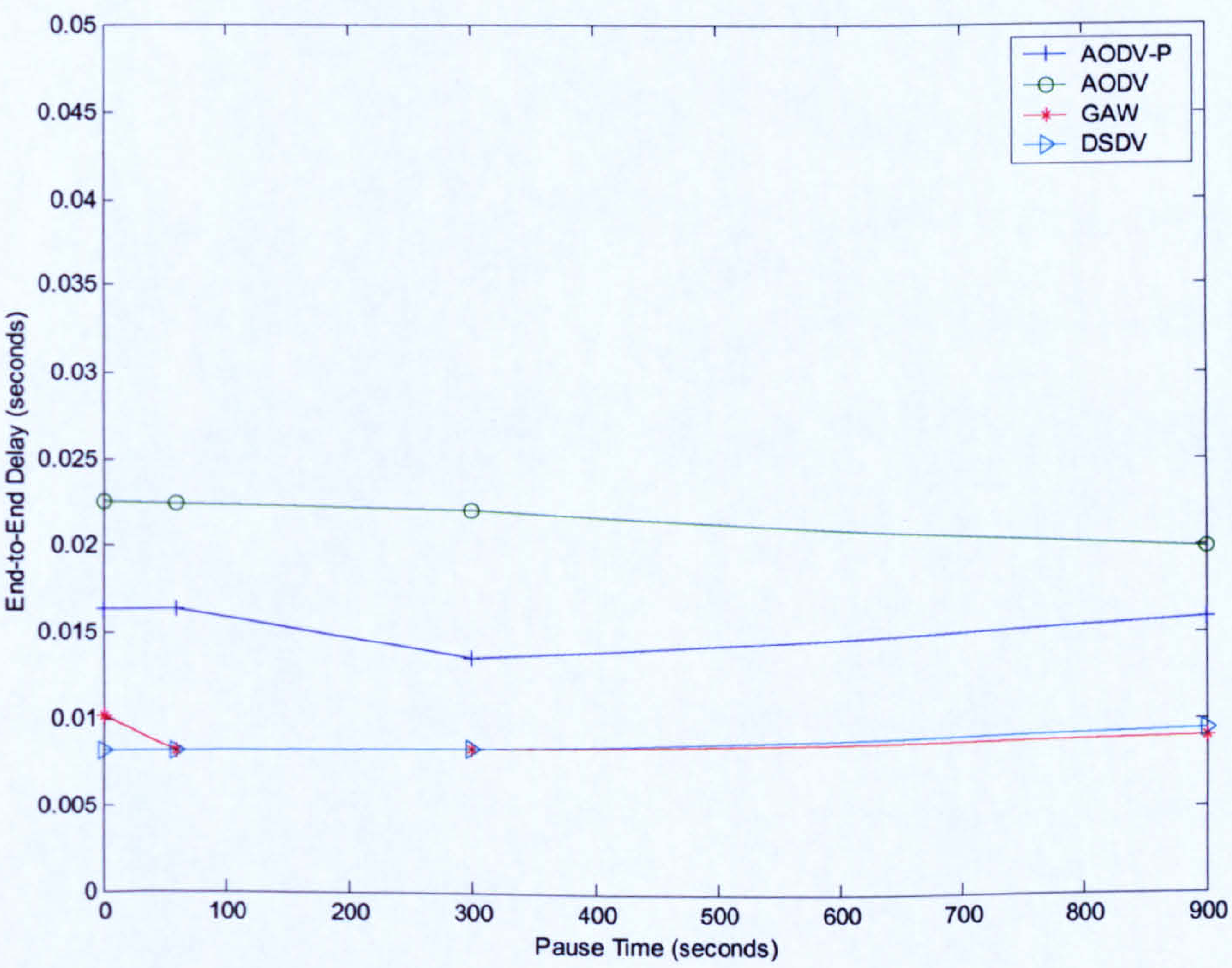



*Figure 5.22 Average End-to-End Delay time vs. node's mobility for IG at (450, 150)*

### *E. More Data Sources*

The simulations shown in the previous sections all use 10 randomly selected data sources at 1 packet per second. In order to investigate the route discovery ability and routing overhead, more data sources are used as a way to increase the data packets transmitted in the network. This is equivalent to increasing the data transmission rate in the network. The following results show the performance with 10, 20 and 30 data sources sending data from different locations. The IG was placed at (0,0). More detailed analysis of AODV with various data source numbers and data rate can be found in [107].

Shown in Figures 5.24-5.26, the packet delivery ratio for *AODV-P*, *AODV*, GAW and *DSDV* does not changes as the number of sources increases, showing that none of them suffer a congestion problem for the level of traffic load.

Figures 5.27-5.30 show the routing overhead of *AODV-P*, *AODV*, GAW and *DSDV* with different data sources. Clearly for the reactive routing protocol more data sources mean more possible route discovery and more route restoration. So for *AODV-P* and *AODV*, the overhead for 10, 20 and 30 sources increases. The amount of additional overhead is much larger and even more than the GAW and *DSDV* when the node mobility is high. In the case of no mobility, the increased source number still adds an overhead to the network. GAW and *DSDV* routing update all the routes regardless of whether they are requested or not, so there are virtually no difference where the source number is increased for them.

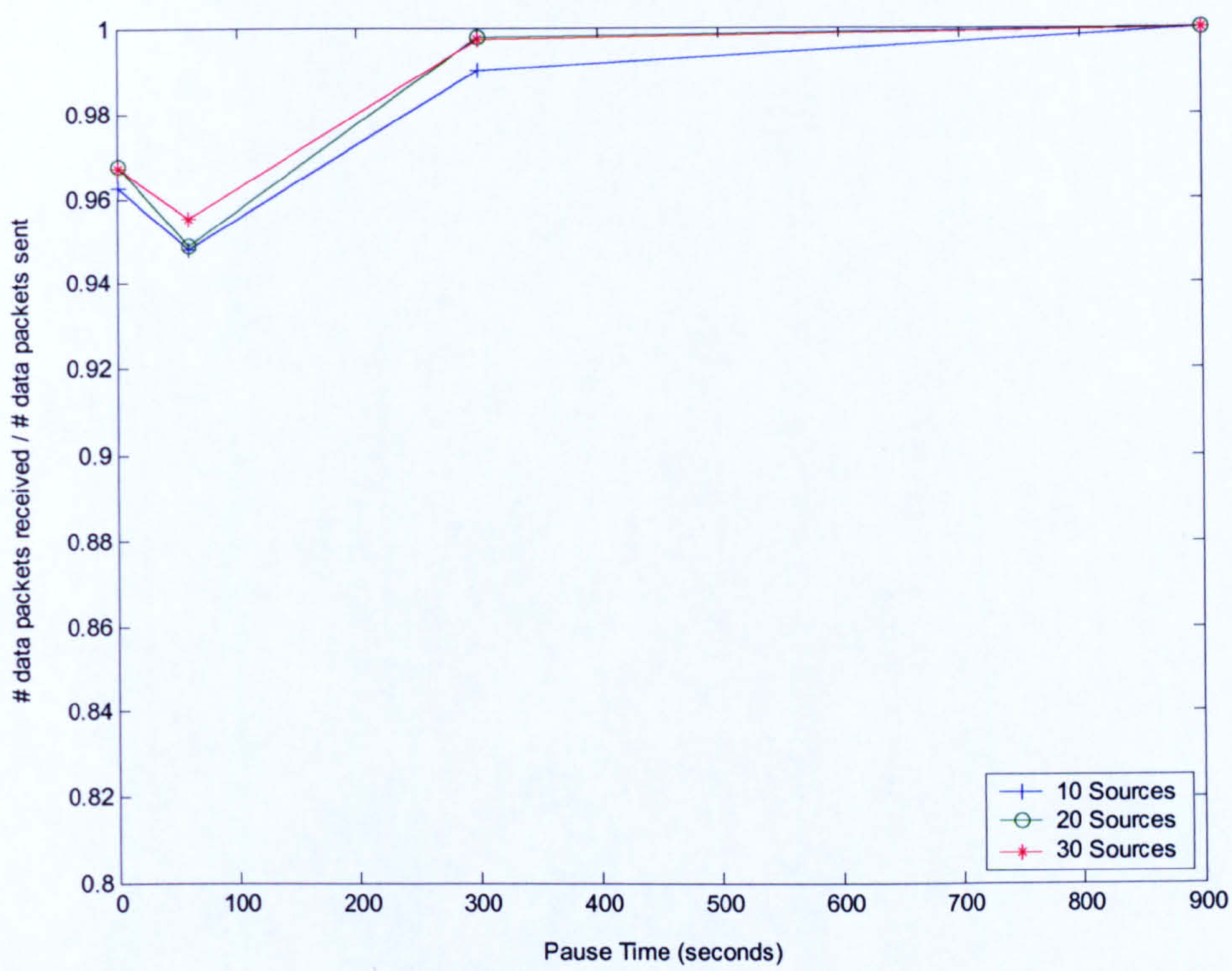



*Figure 5.23 Packet delivery ratio of AODV-P vs. node's mobility for IG at (0, 0)*

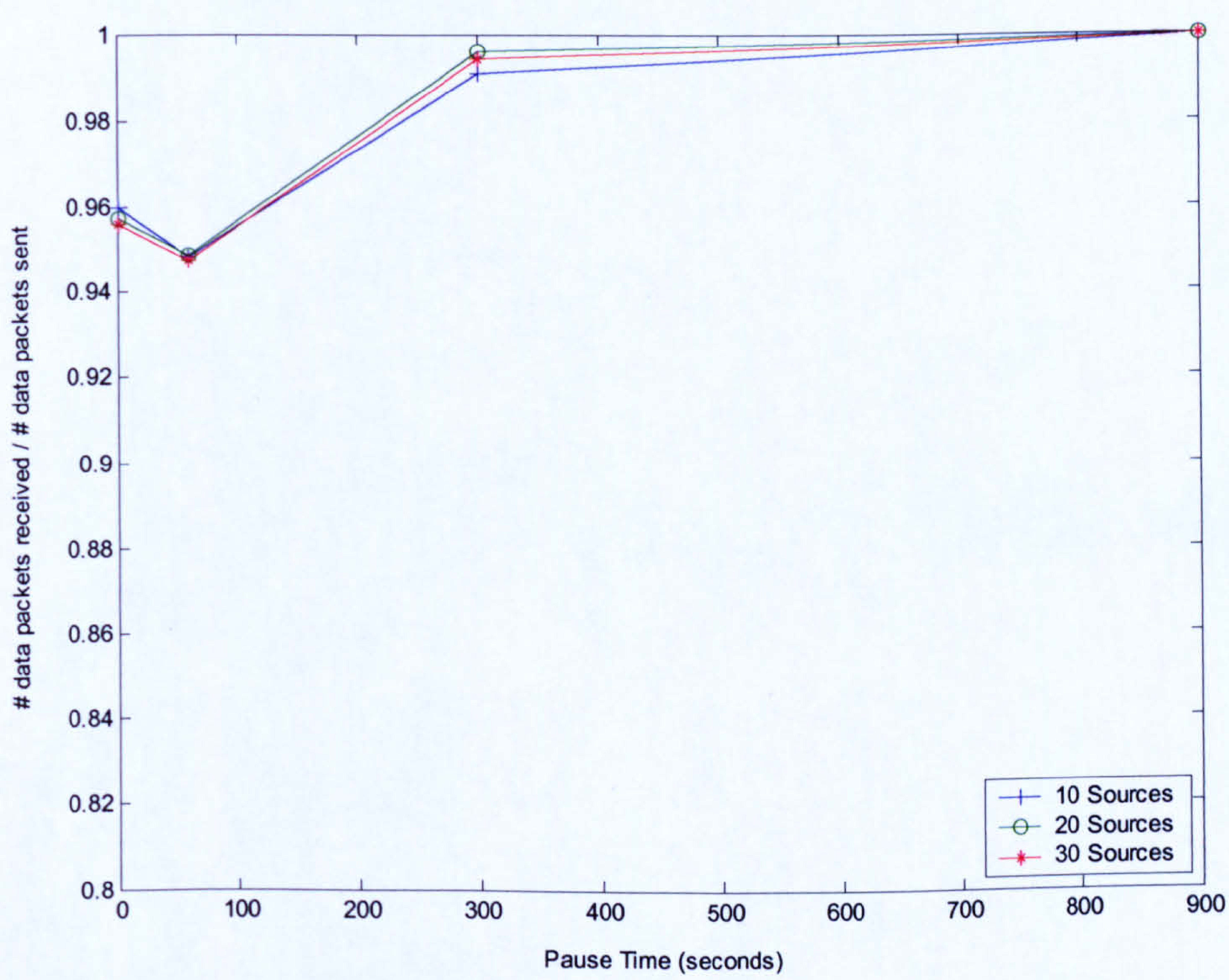



*Figure 5.24 Packet delivery ratio of AODV vs. node's mobility for IG at (0, 0)*

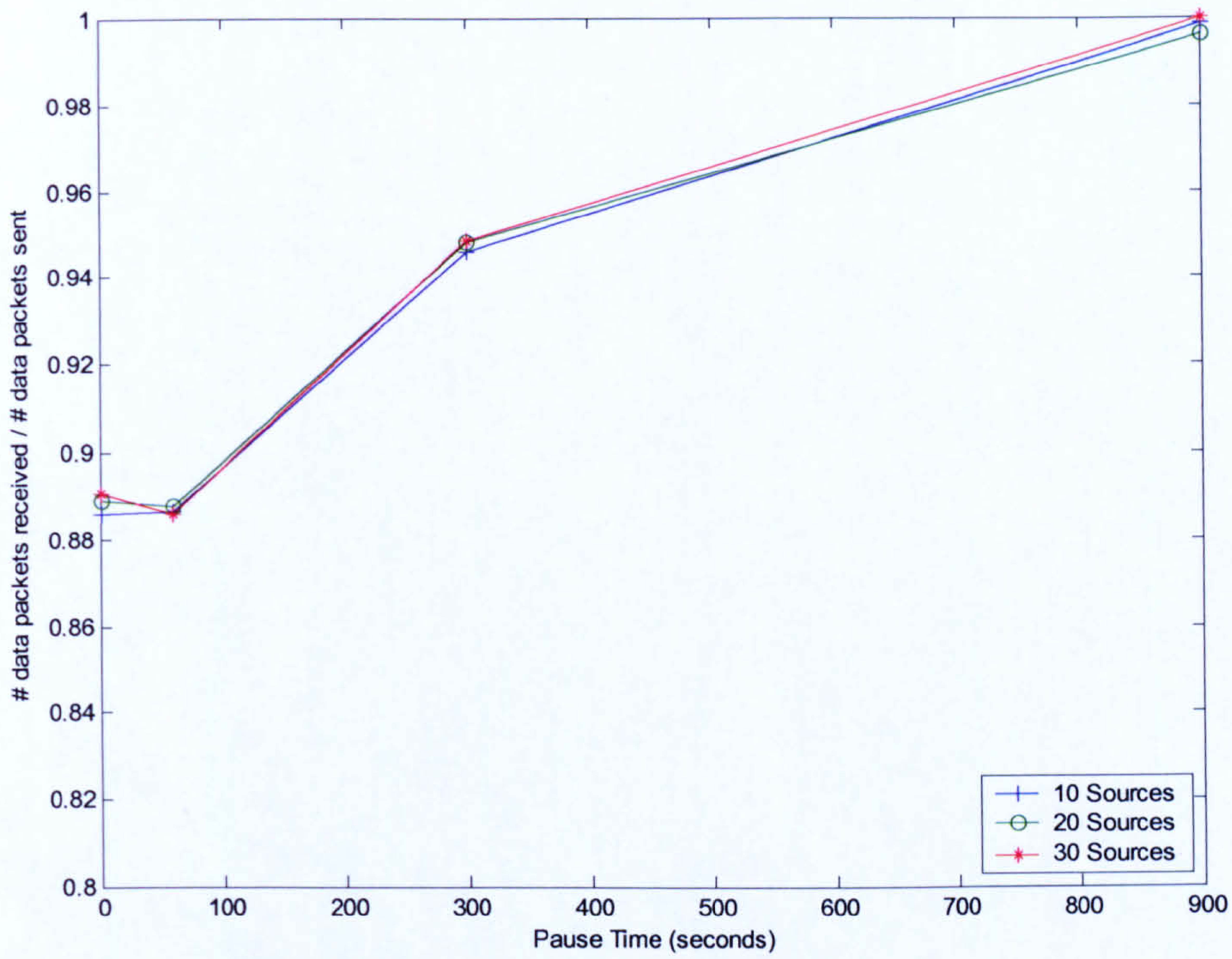



*Figure 5.25 Packet delivery ratio of GAW vs. node's mobility for IG at (0, 0)*

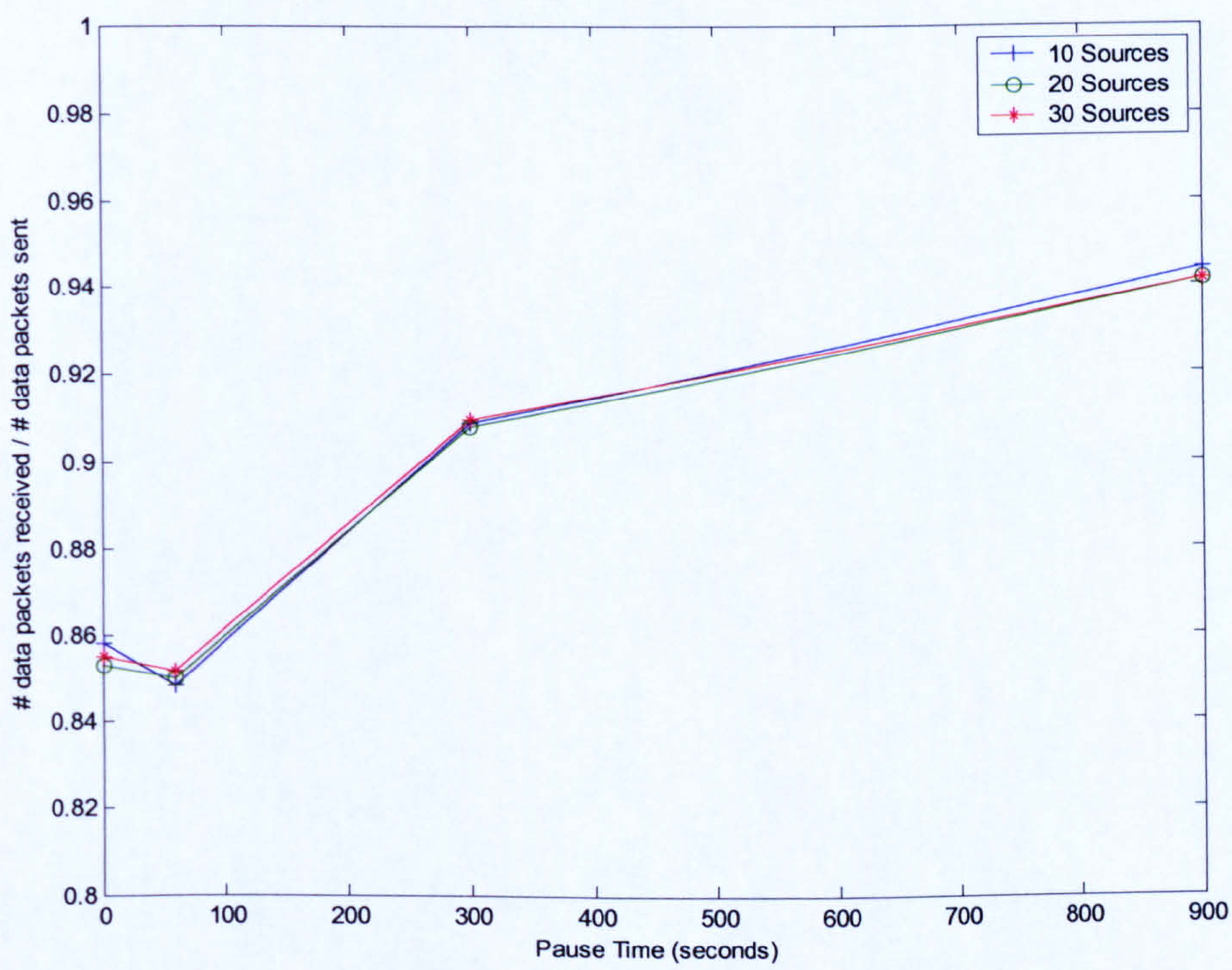



*Figure 5.26 Packet delivery ratio of DSDV vs. node's mobility for IG at (0, 0)*

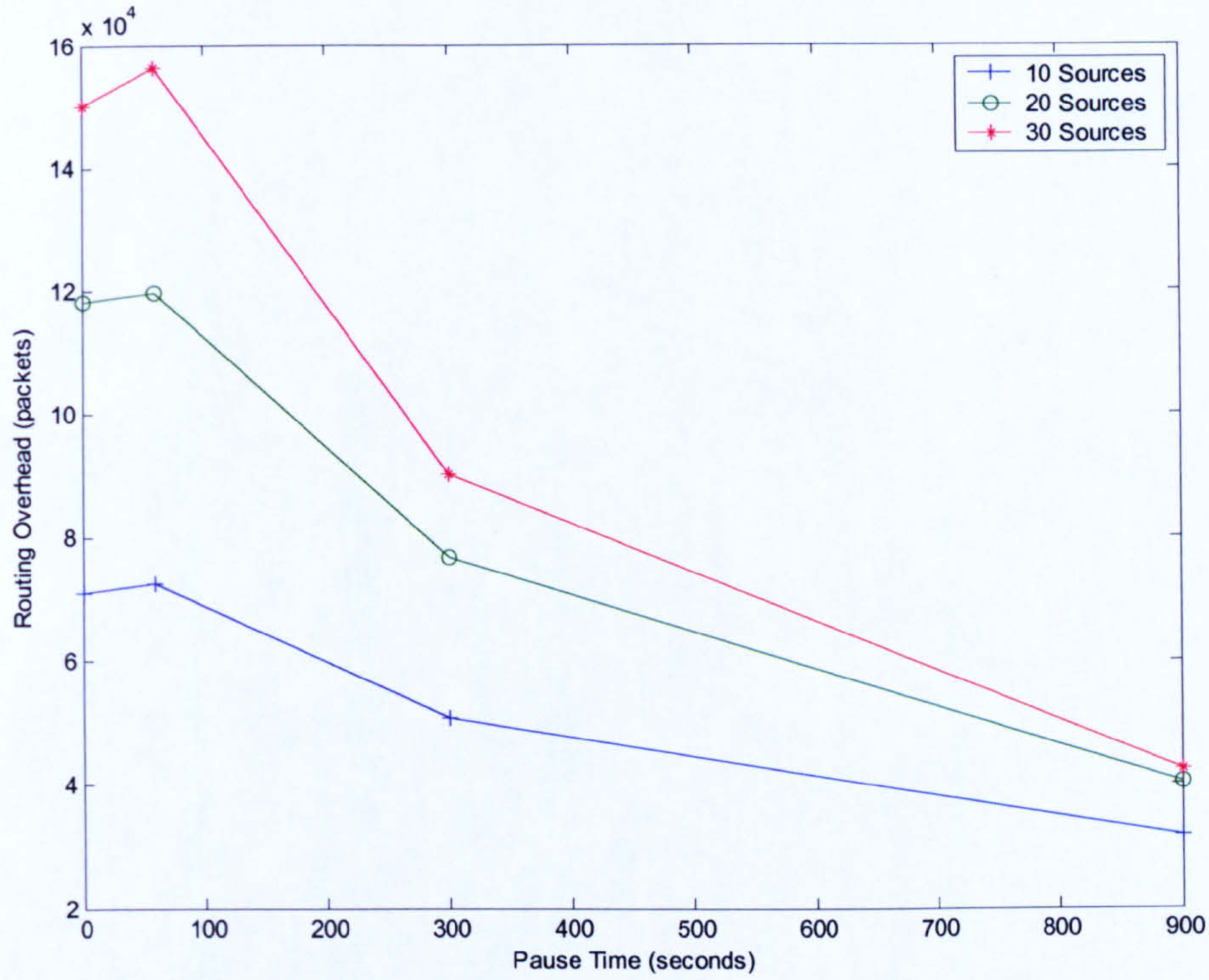



*Figure 5.27 Routing overhead of AODV-P vs. node's mobility for IG at (0, 0)*

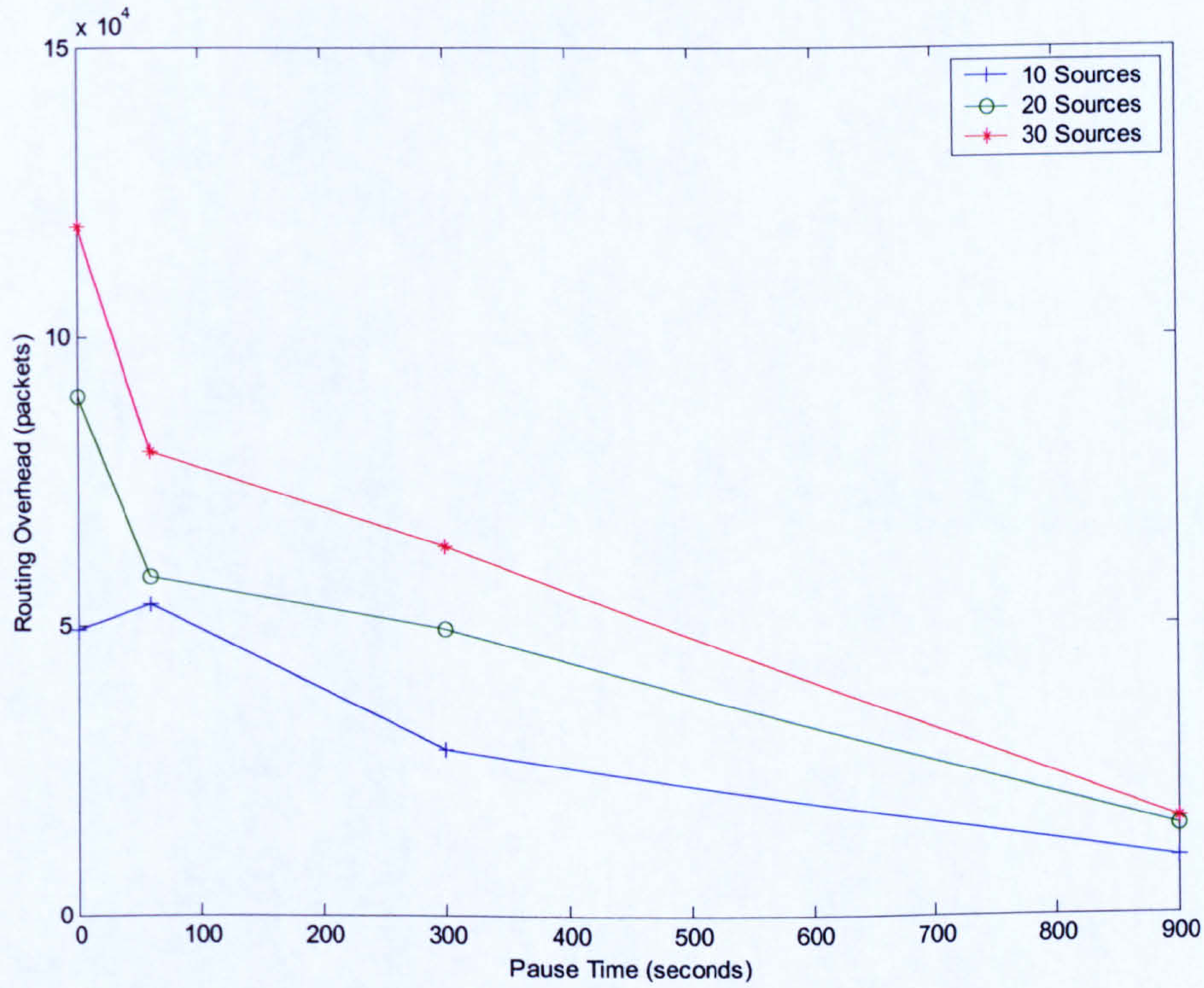



*Figure 5.28 Routing overhead of AODV vs. node's mobility for IG at (0, 0)*

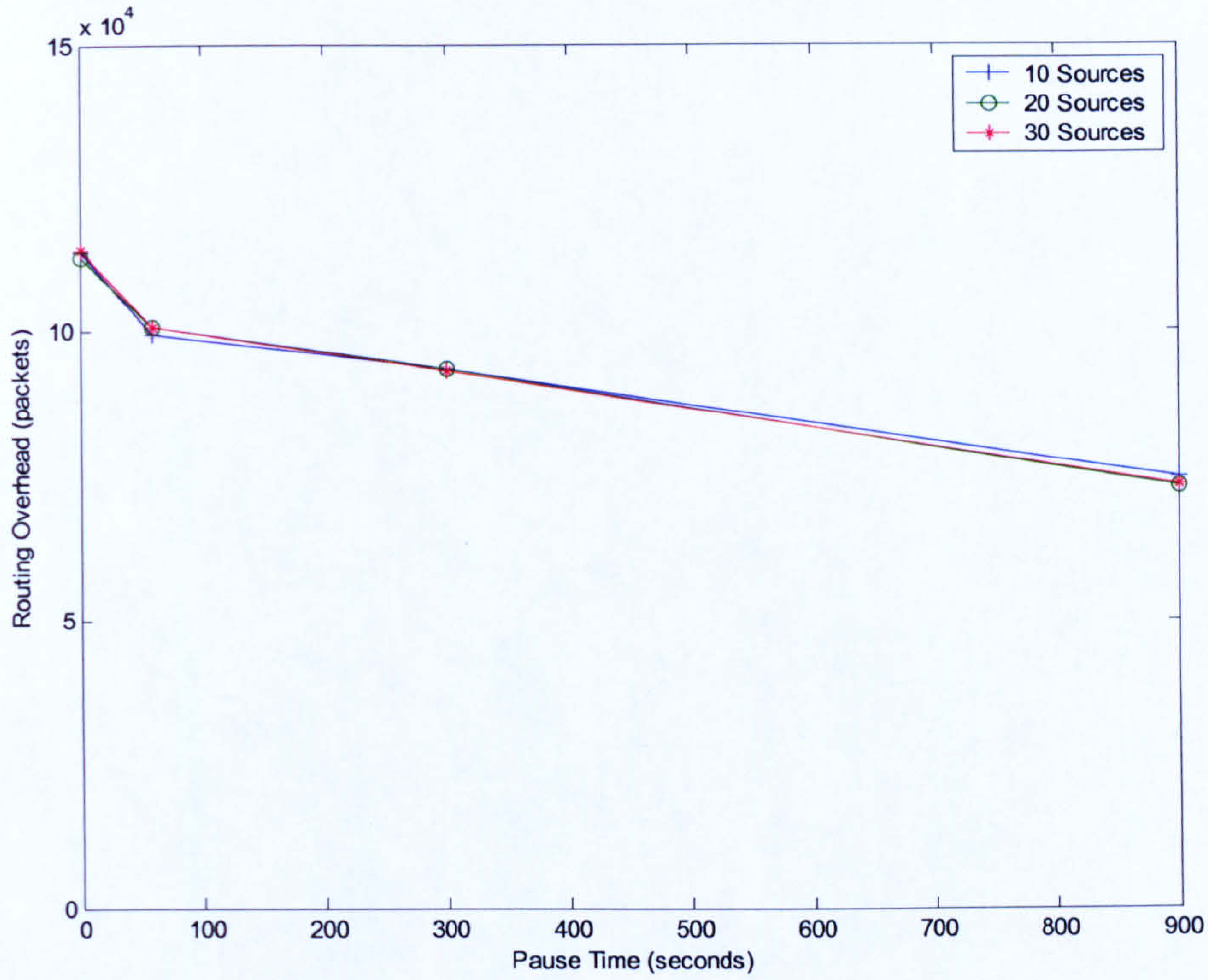



*Figure 5.29 Routing overhead of GAW vs. node's mobility for IG at (0, 0)*

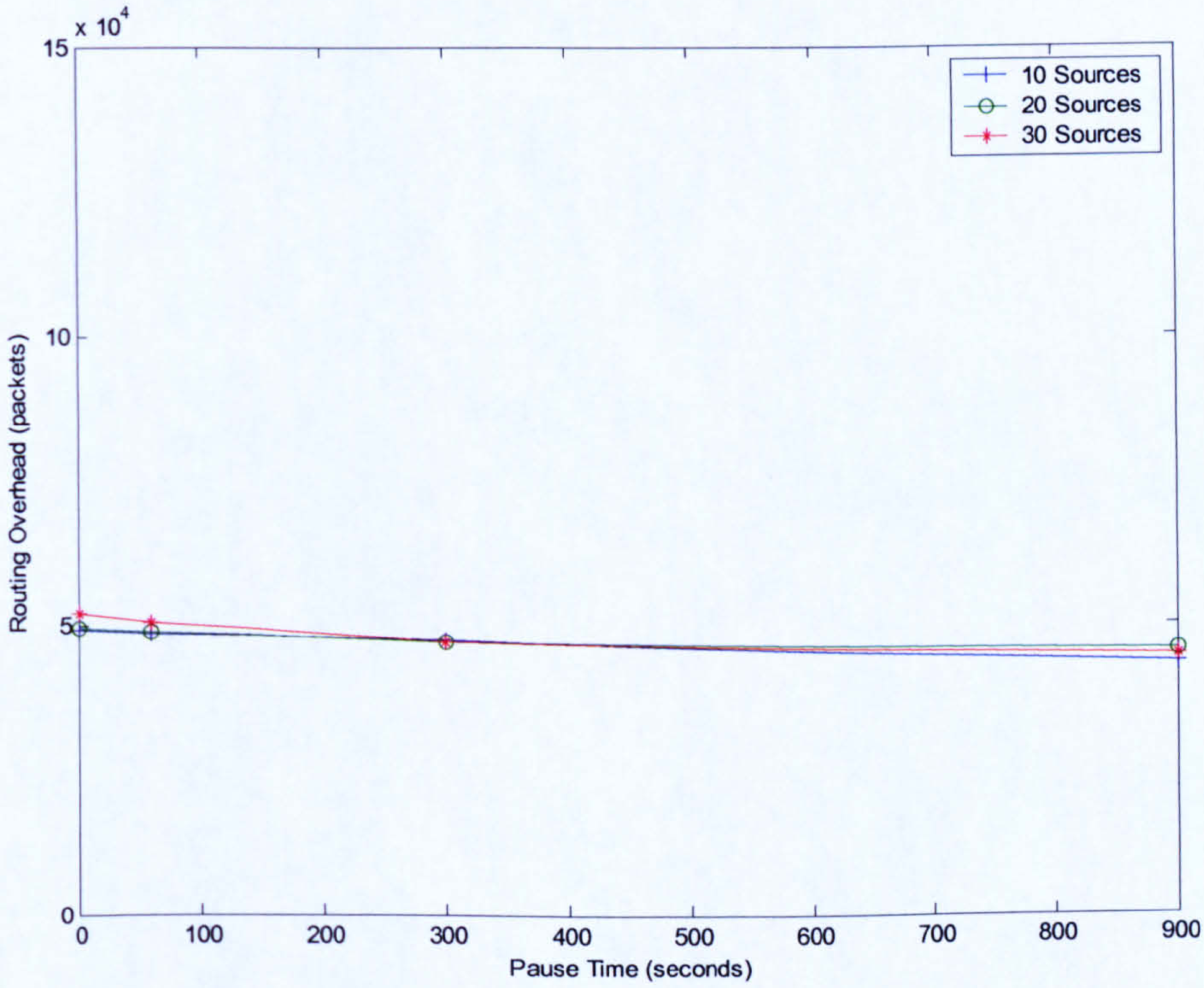



*Figure 5.30 Routing overhead of DSDV vs. node's mobility for IG at (0, 0)*

### 5.4.4 Routing Efficiency and Load Balancing

*A. Routing Efficiency Comparison*

This section investigates the efficiency of each connection method. Depending on the different Ad Hoc routing algorithms, the routes used by different implementations vary considerably. From the packet distribution point of view, the selection of different routes means that different wireless nodes may be involved in delivering the same data packet. By calculating the total number of times and the average number of wireless nodes which are used to deliver all the data packets in the simulation, the routing efficiency between each implementation can be compared. To investigate this issue, results need to be taken from the same scenario files used and the route distributions of packets examined previously.

Since a fair comparison needs to be made for those results with the same amount of data packets being delivered, the scenario files with no node mobility were used. All implementations except *DSDV* have above 99% average packet delivery ratio with total 7486 transmitted data packets. The results of packet delivery ratio in each implementation for different IG locations are shown in Table 5.6.

*Table 5.6 Packet Delivery Ratio of Results Used*

| IG Locations | AODV-P | AODV | GAW | DSDV |
|---|---|---|---|---|
| IG (0,0) | 0.99996 | 0.99861 | 0.99833 | 0.94408 |
| IG (200,100) | 0.99948 | 0.99939 | 0.99993 | 0.97896 |
| IG (450,150) | 0.99999 | 0.99999 | 0.99869 | 0.97962 |

*Chart 5.1 Total Packets Transmitted in the Network*

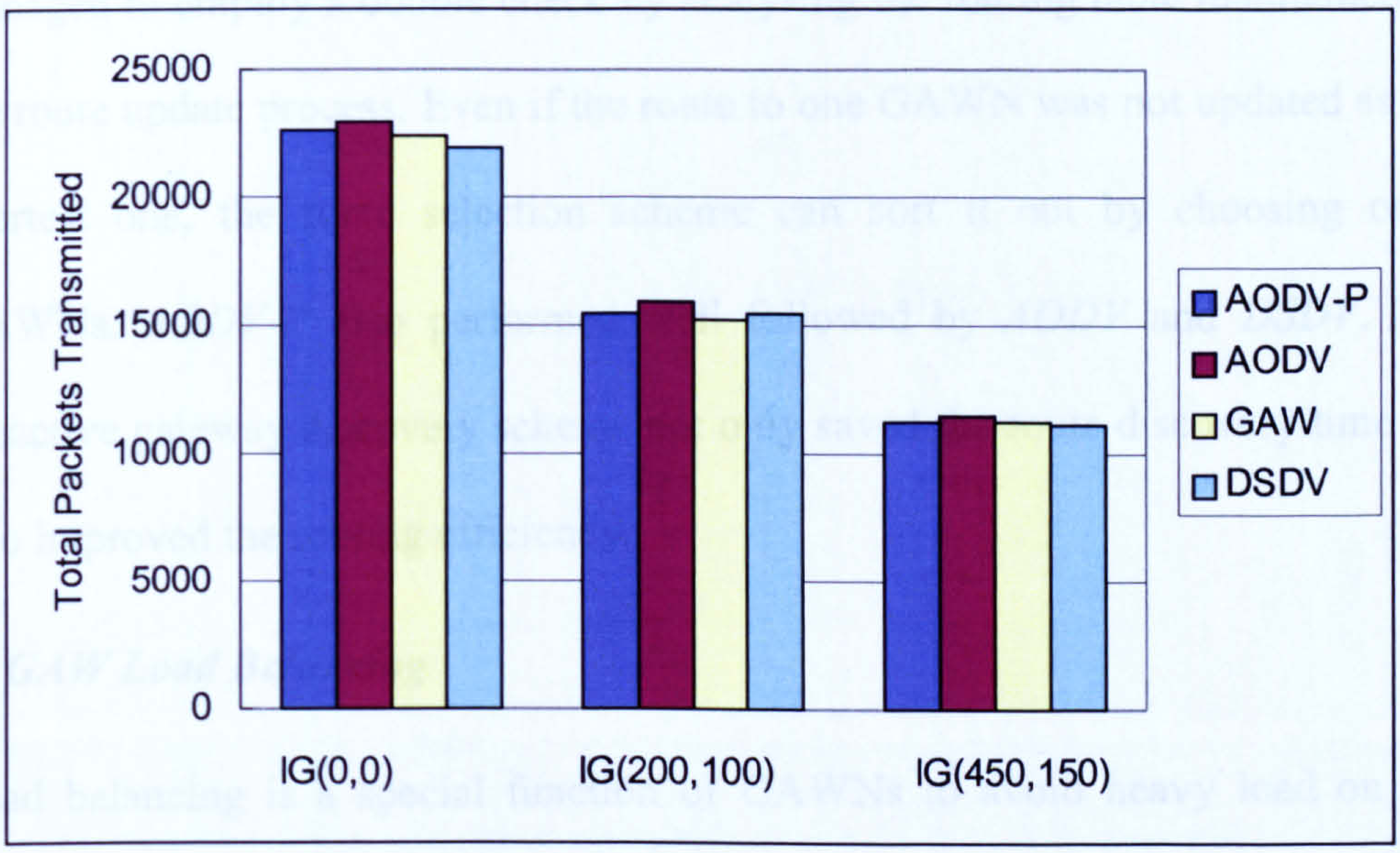



*Chart 5.2 Normalised Average Number of Hops from Sources to Internet*

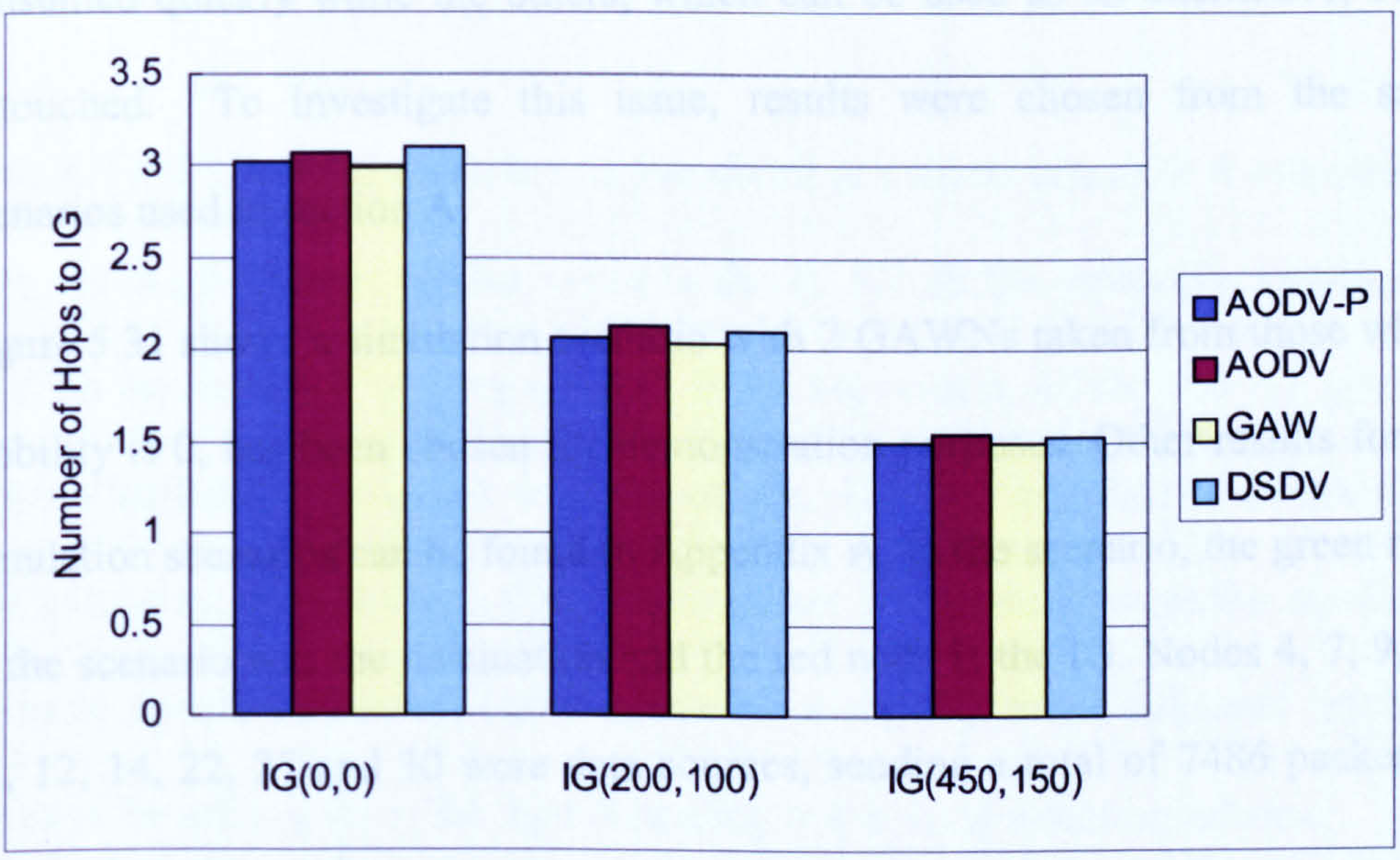



Chart 5.1-5.2 summarise the routing efficiency of each implementation. The average number of hops was calculated from the total number of packets used and the packet delivery ratio. The results show that, no matter the position of IG, the GAW routing method offered the best routing efficiency with smaller packet

delivery times and fewer hops from sources to the Internet. The advantage of having the layer of GAWNs is clearly shown. The GAW route selection scheme managed to employ a double check by analysing the routing table maintained by the route update process. Even if the route to one GAWN was not updated as the shortest one, the route selection scheme can sort it out by choosing other GAWNs. *AODV-P* also performed well followed by *AODV* and *DSDV.* The proactive gateway discovery scheme not only saved the route discovery time but also improved the routing efficiency.

***B. GAW Load Balancing***

Load balancing is a special function of GAWNs to avoid heavy load on any particular node. An unbalanced load may result in some nodes' power being consumed quickly while the others, which can be used as an alternative, being untouched. To investigate this issue, results were chosen from the same scenarios used in section A.

Figure 5.31 shows a simulation scenario with 2 GAWNs taken from those where mobility is 0, has been chosen for demonstration purposes. Other results for the simulation scenarios can be found in Appendix A. In the scenario, the green node in the scenario was the destination and the red node is the IG. Nodes 4, 7, 9, 10, 11, 12, 14, 22, 27 and 30 were data sources, sending a total of 7486 packets of data to the green node.

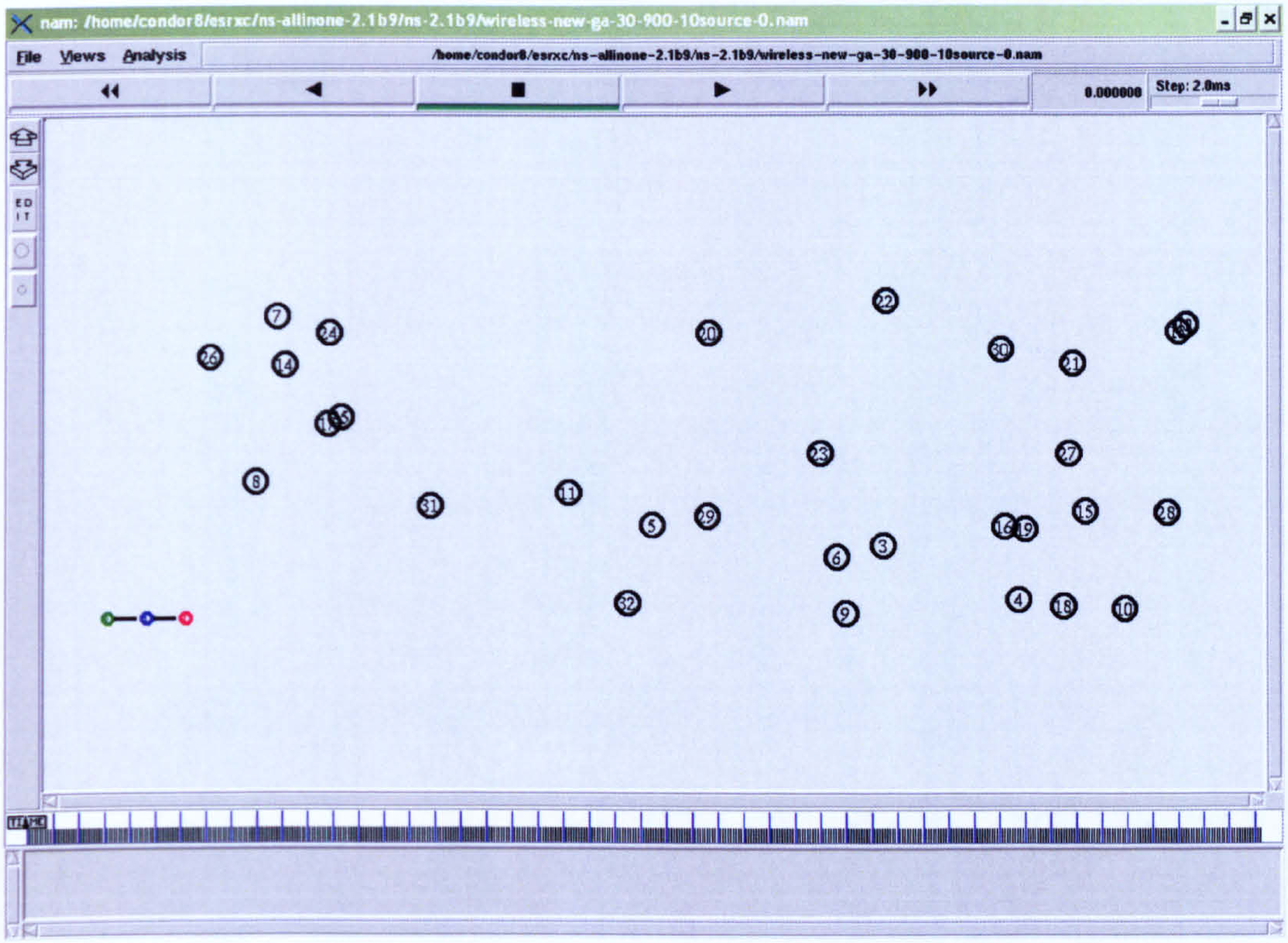


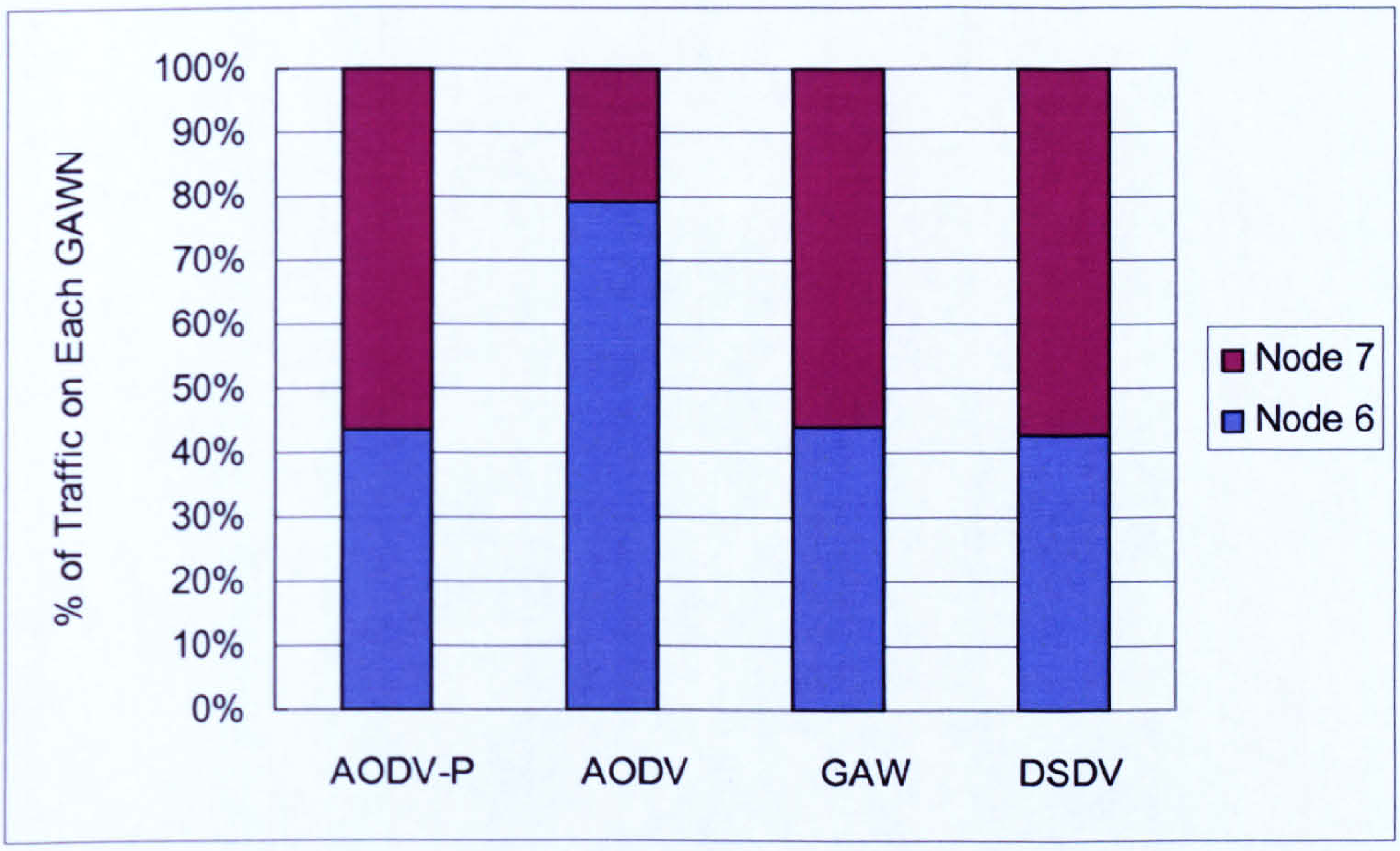
*Figure 5.31 Screen shot for simulation scenario*

Table 5.7 and Chart 5.3 show the packet distribution between node 6 and node 7. They are the final hops on the routes to the IG for all the protocols, working as GAWNs for the GAW routing method. From the results, *AODV* was not good at packet distribution compared with the others. *AODV-P* and *DSDV* do not have load balancing on route selection. Their packet distributions were the results of the route update processes. GAW produced a slightly better balanced result in this case; benefiting from the load balancing in the route selection scheme.

*Table 5.7 Number of node used among GAWNs*

| GAWNs | AODV-P | AODV | GAW | DSDV |
|---|---|---|---|---|
| Node 6 | 3275 | 5926 | 3308 | 2997 |
| Node 7 | 4210 | 1560 | 4178 | 4003 |
| Total | 7485 | 7486 | 7486 | 7000 |

*Chart 5.3 Packets distribution among GAWNs*




## 5.4.5 Conclusion

### *A. IG's Broadcast Interval*

From the simulation results in 5.3.2, it is clear that the IG broadcast interval affects the protocols using the proactive gateway discovery scheme in both packet delivery ratio and routing overhead. The effects are not that obvious in the packet delivery ratio of *AODV-P;* but change the performance of *DSDV* dramatically. With a carefully selected GAW state change timer, the GAW routing method shows a robust and stable performance; again the IG's broadcast interval change. Considering the routing overhead, *AODV-P* was flooded when the IG's broadcast interval was short. The overheads of GAW and DSDV are dominated by the periodic update messages and use a method to block the flooding so the effects from IG's broadcast were not that obvious.

### *B. Overall Performance*

Section 5.4.3 analyses the performance of the MANET to Internet communication for different implementations. Generally speaking, all protocols tend to perform better in terms of packet delivery ratio when the node's mobility is lower. The position of the IG changes the performance of all the implementations. An IG in the middle of the network can maximise the overall performance of all the MANET to Internet communications.

In the simulations, the GAW routing method exhibited a little more routing overhead than *DSDV;* to offer a much better packet delivery ratio. The GAW route update method managed to accomplish the update without causing the huge overhead seen in *DSDV-S*. Its routing overhead was constant regardless of the demand for higher data traffic. The average end-to-end delay time of GAW is also much shorter than *AODV-P* and *AODV*. On the other hand, both *AODV-P* and *AODV* achieved better packet delivery ratio than GAW, *DSDV-S* and *DSDV* while suffering a long delay spent on the route discovery. Their routing overhead appeared to increase as the traffic demand increased.

### *C. Routing Efficiency and Load-balancing*

The unique route selection method of GAW minimises the possibility of inaccurate routing information by offering a layer of well-maintained GAWNs which resulted in the best routing efficiency in the simulations. Furthermore, GAW is the only method involving the load balancing among GAWNs. Other methods depend solely on the routing update methods to manage the route. The GAW routing method employs load balancing in the route selection process to ensure optimised packet distribution.

# 5.5 Simulations from Internet to MANET

## 5.5.1 Overview

In this section of the thesis, simulations for Internet to MANET communication are introduced. All this work has been done using the general simulation setup described in section 5.3. As discussed in section 5.2.2, an extra registration process may be needed to enable Internet to MANET communication for the AODV routing protocol. Therefore, only GAW and *DSDV* were implemented to cope with the communication requirement from the Internet to a MANET.

The results are to be shown in two parts. In the first part, section 5.5.2, the results show the performance of GAW and *DSDV* when the IG's broadcast period varies from 0 to 60 seconds. The individual results of packet delivery are analysed. It is apparent that both GAW and DSDV used proactive route update, which is irrelevant to the communication types. So, the routing overheads, the equivalent to the performances in section 5.3.2, will not be shown. Apart from the IG's broadcast period, the influence of mobile nodes' mobilities are shown as well. The same simulations have been carried out for node mobilities of 0, 60, 300 and 900 seconds and more detailed analysis is given in part two.

In the second part, in-depth comparisons are given for all the protocols when the IG's broadcast period is fixed at 10 seconds and node mobilities vary from 0 to 900 seconds. Results for the IG locations as used previously, namely (0,0), (200,100) and (450,150) are compared with the MANET to Internet communication.

## 5.5.2 Performance vs. IG Broadcast Interval

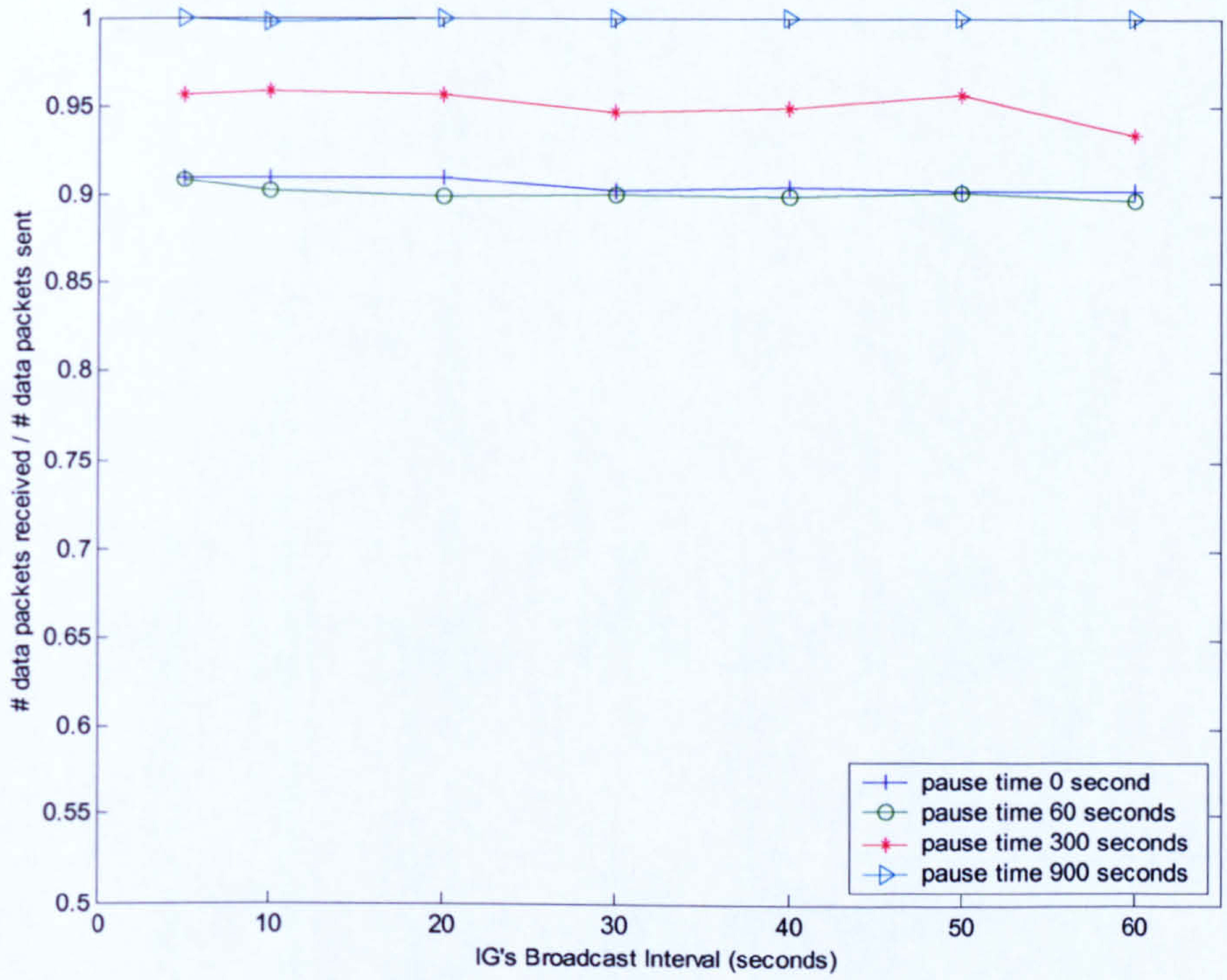



*Figure 5.32 Packet delivery ratio of GAW, from Internet to MANET with IG at (0,0)*

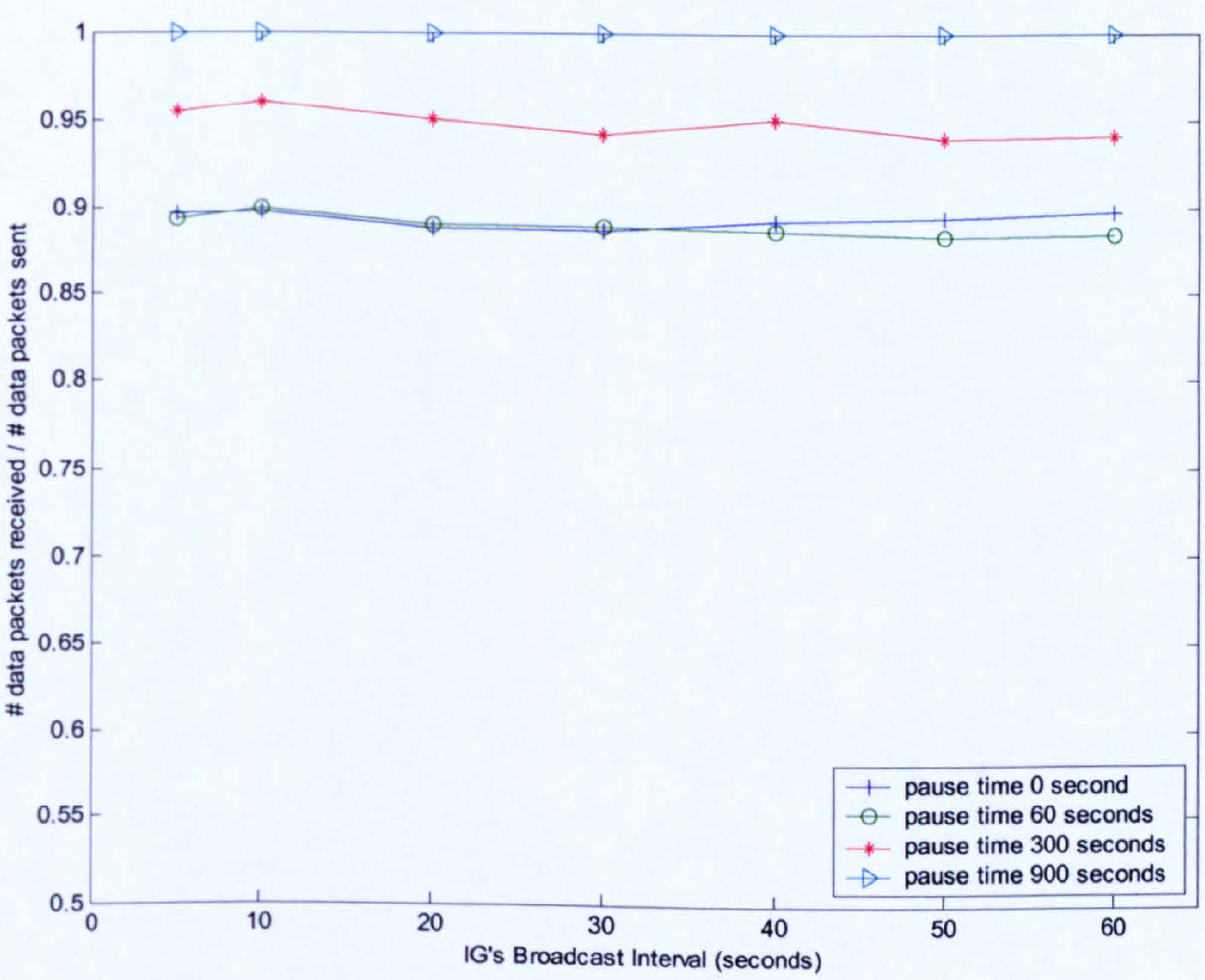



*Figure 5.33 Packet delivery ratio of DSDV, from Internet to MANET with IG at (0,0)*

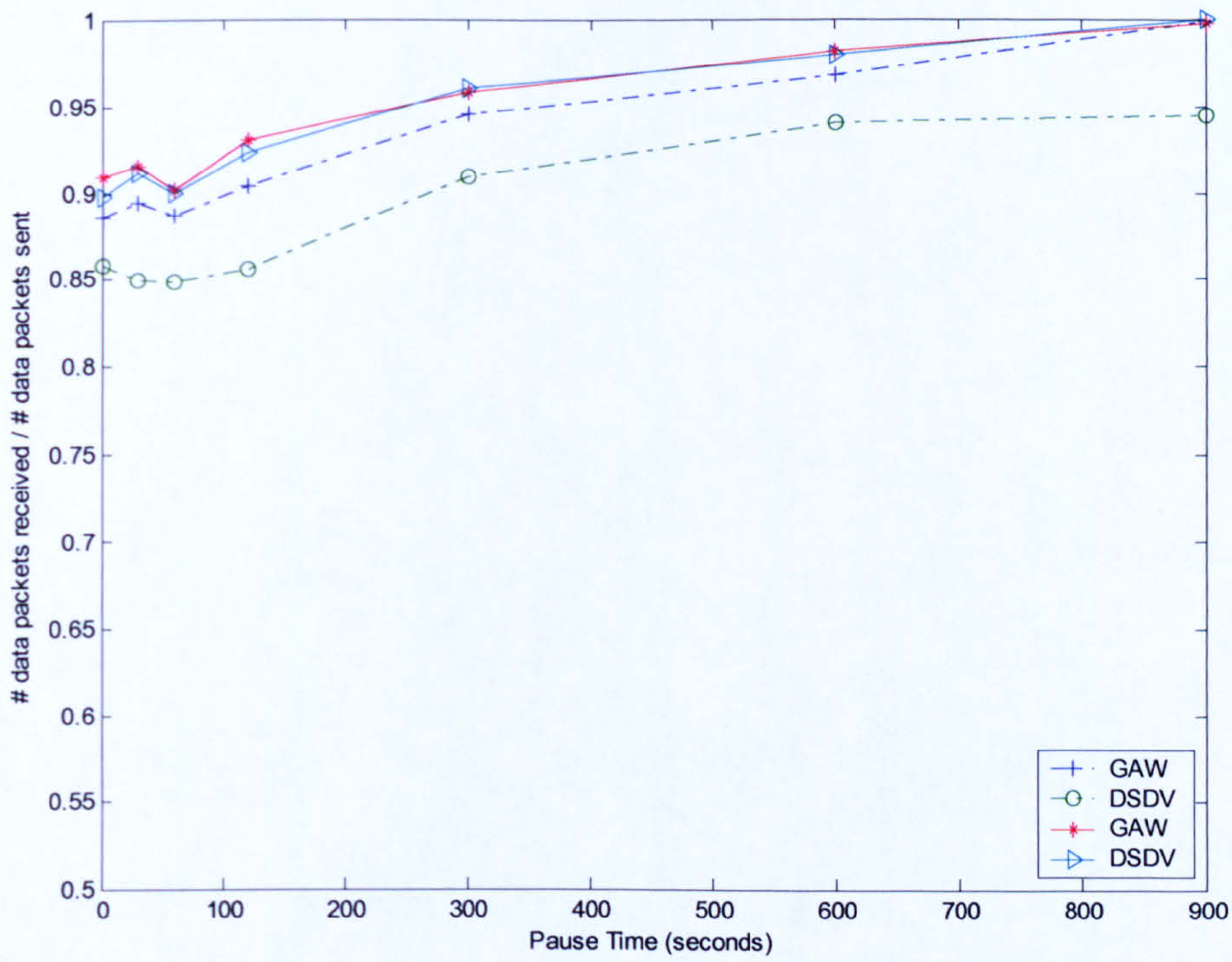



*Figure 5.34 Packet delivery ratio comparisons for IG at (0,0)*

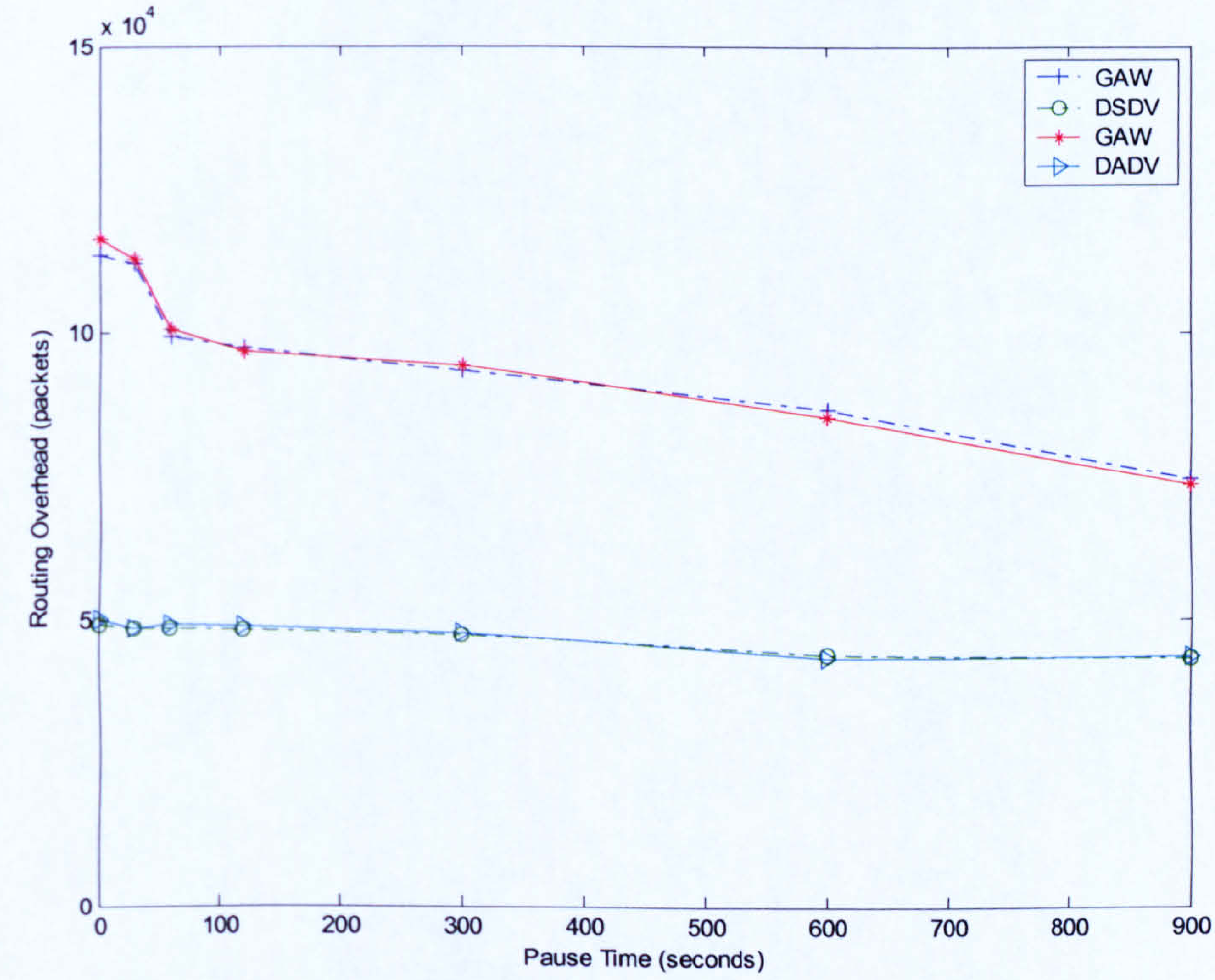



*Figure 5.35 Routing overhead comparisons for IG at (0,0)*

Through the route update process of GAW and *DSDV*, the IGs gain routes to all approachable wireless nodes in the Ad Hoc domain. These update process are irrelevant to the IG's broadcast interval. In other words, the IG's broadcast interval changes do not change the routing table update of IGs. Figures 5.32-33 show that to both GAW and *DSDV*, no matter what the broadcast interval, the packet delivery ratio did not change. However, the results have more differences compared with the MANET to Internet communication in section 5.4.2. The analysis will be given in section 5.5.3.

### 5.5.3 Overall Performance

#### *A. Simulation Setup*

This section compares the performance of Internet to MANET connection for GAW and *DSDV* as the wireless node's mobility varies. The position of the IG has also been examined as described in section 5.4.

*Table 5.8 Parameters of Overall Comparison for Internet to MANET Simulation*

| Parameter | Value |
|---|---|
| Protocols | DSDV, GAW |
| Source(s) | 1 Wired Node |
| Destination(s) | 10 Wireless Nodes |
| Number of Wired Nodes | 3 |
| IG Position | (0,0) (200,100) (450,150) |
| IG Broadcast Interval | 10 Seconds |

Although the IG's broadcast interval does not affect the Internet to MANET performance, it is fixed at 10 seconds for continuity with section 5.4.3. The locations of the IG have been again chosen from the far end to the middle of the network topology to see the effect of IG locations on the performance of the routing protocols. Both GAW and *DSDV* have been simulated with the pre-generated 70 scenario files. Some key parameters are shown in Table 5.8.

***B. Performance comparison with IG at (0,0)***

Figure 5.34 compares the packet delivery ratio of GAW and *DSDV* with 2 way communications. The solid line represents the Internet to MANET communication and the dash dot line represents the MANET to Internet communication. Considering that the route update method used by GAW and *DSDV* to the IG are the same, they achieved nearly the same performance when communication is set from the Internet to MANET. The delivery ratio is better compared with the MANET to Internet communication. It has average 1% improvement for GAW and a larger 5-10% improvement for *DSDV*. Generally speaking, the reason is that in both methods the source queues the packets for the unknown wireless destinations until a route becomes available; whilst in MANET to Internet communication the packets for unknown Internet address are dropped. However, the queuing may result in a delay before transmission as shown in Figure 5.36.

The routing overheads in Figure 5.35 show little difference from those for MANET to Internet communication. In fact, since both GAW and *DSDV* use the proactive routing method, the routing overhead should be the same regardless of the communication types. In Figure 5.36, the delay time is slightly longer than the Internet to MANET case since packet queues occur to delay the packets. The results for GAW were more comparable since its packet delivery ratios were less changed. Depending on the node mobility, some packets that did not reach the destinations were still queuing on the source, or have been dropped, due to the wrong route being received by the IG. As discussed before, the packet delivery ratio and end to end delay are not independent and should be considered together when examining these figures.

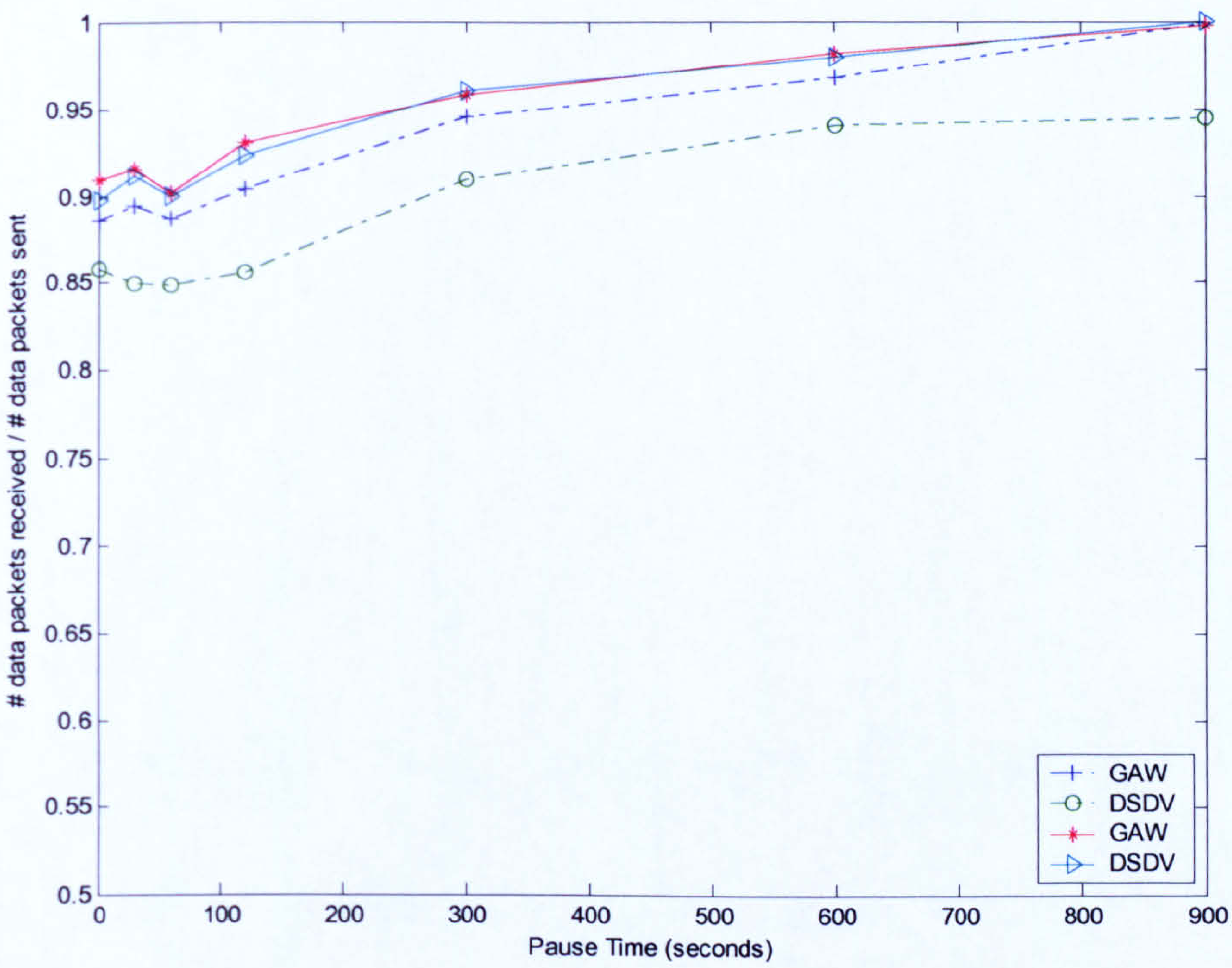



*Figure 5.34 Packet delivery ratio comparisons for IG at (0,0)*

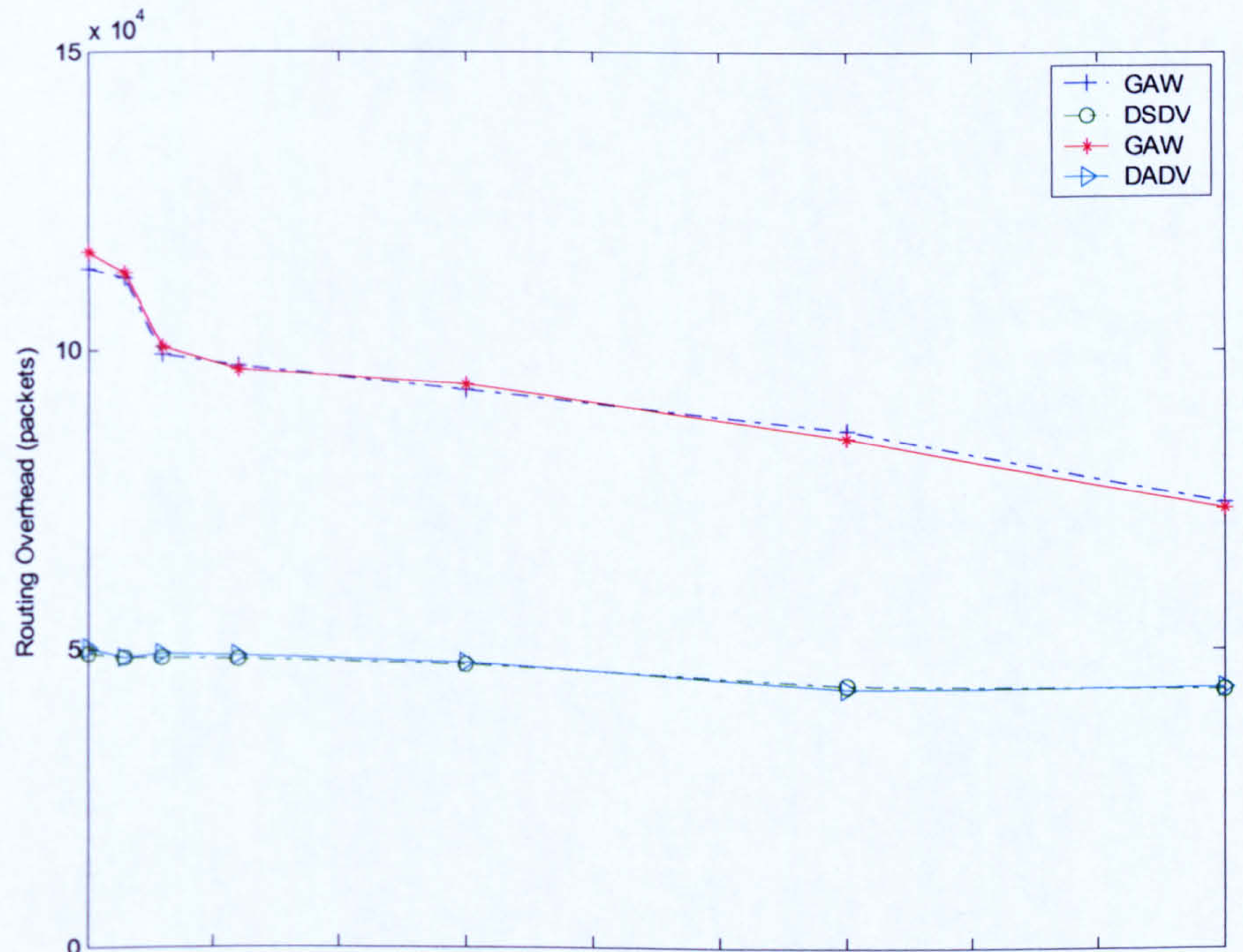



*Figure 5.35 Routing overhead comparisons for IG at (0,0)*

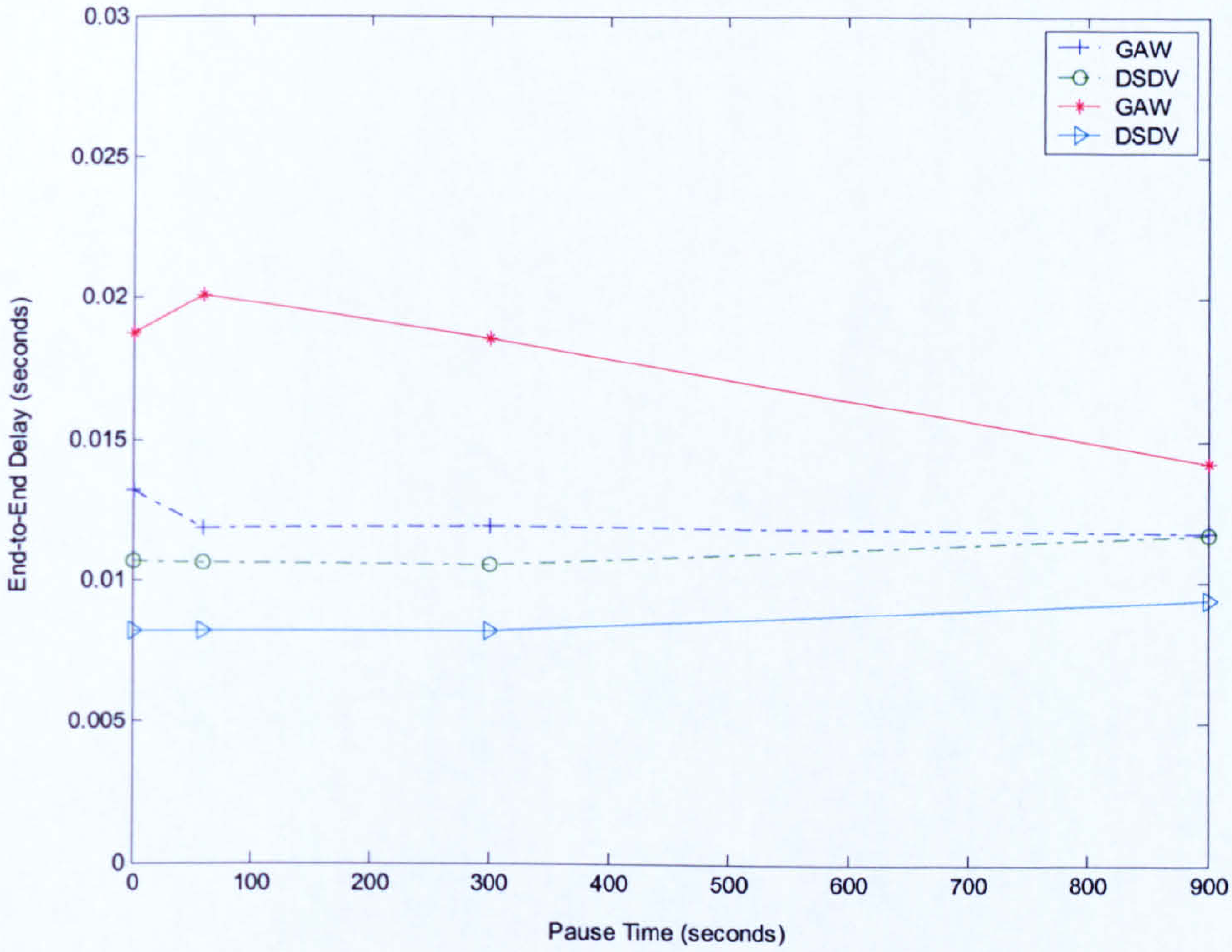



*Figure 5.36 Average End-to-End Delay time comparisons for IG at (0,0)*

***C. Performance comparison with IG at (200,100)***

Figures 5.37-5.39 show the comparisons when the IG was located at (200,100). In this case, the number of available routes between the Internet and MANET is increased. The results clearly show the effects of this change. The packet delivery ratio of both GAW and *DSDV* was improved with the sources on the Internet. Their routing overheads performed the same as when the sources were in the MANET. The delay times of the source queue were less compared with the results in section B.

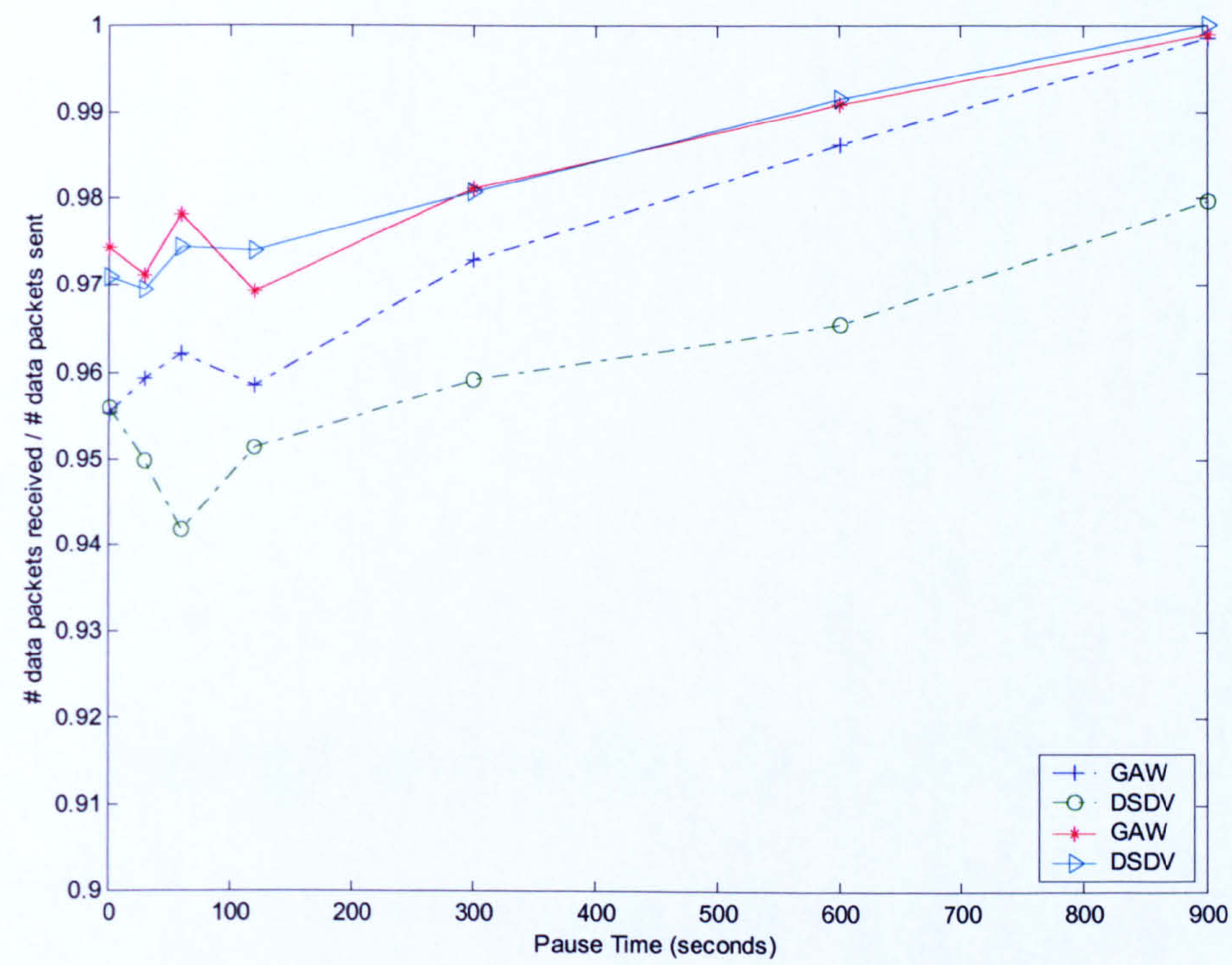



*Figure 5.37 Packet delivery ratio comparisons for IG at (200,100)*

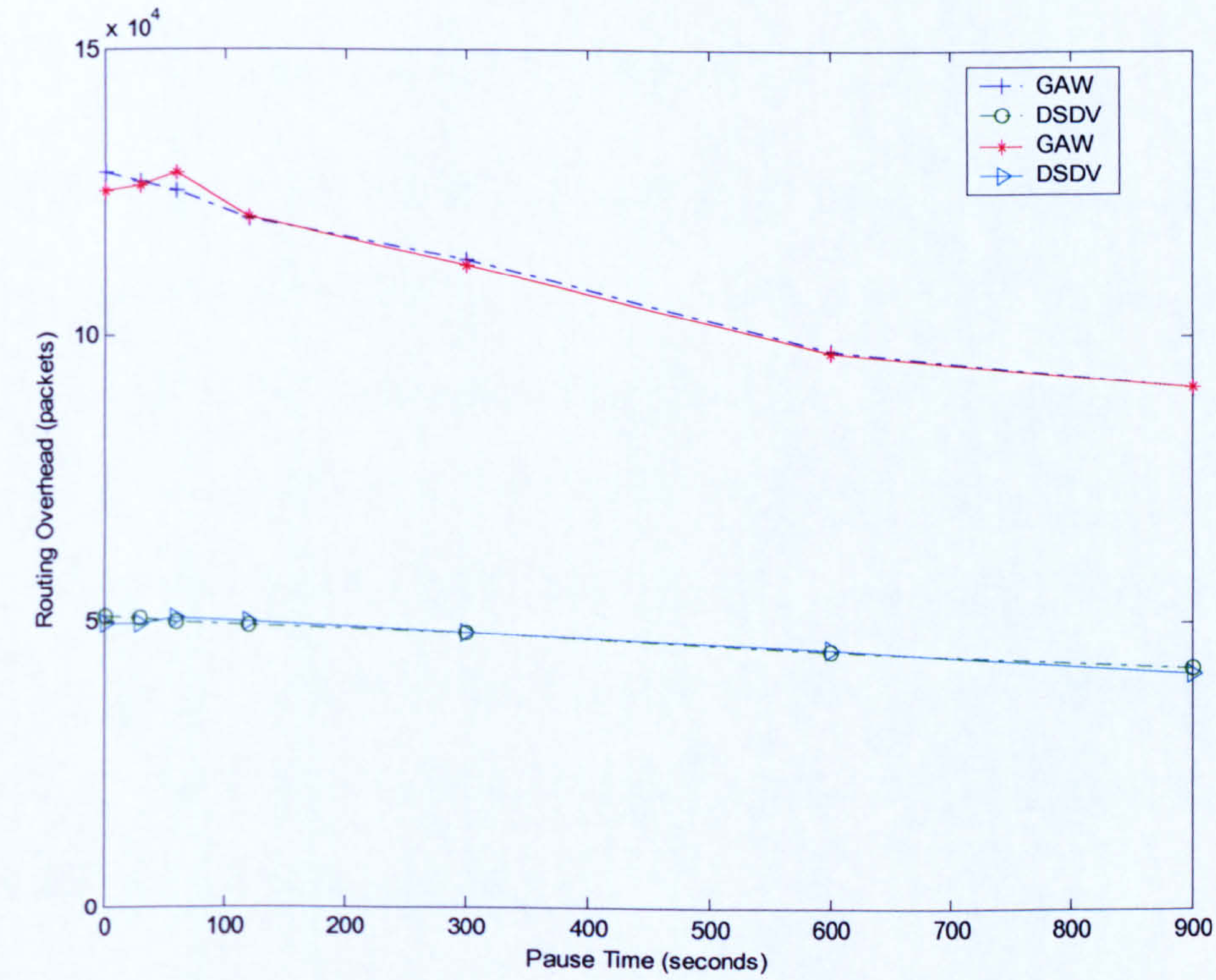



*Figure 5.38 Routing Overhead comparisons for IG at (200,100)*

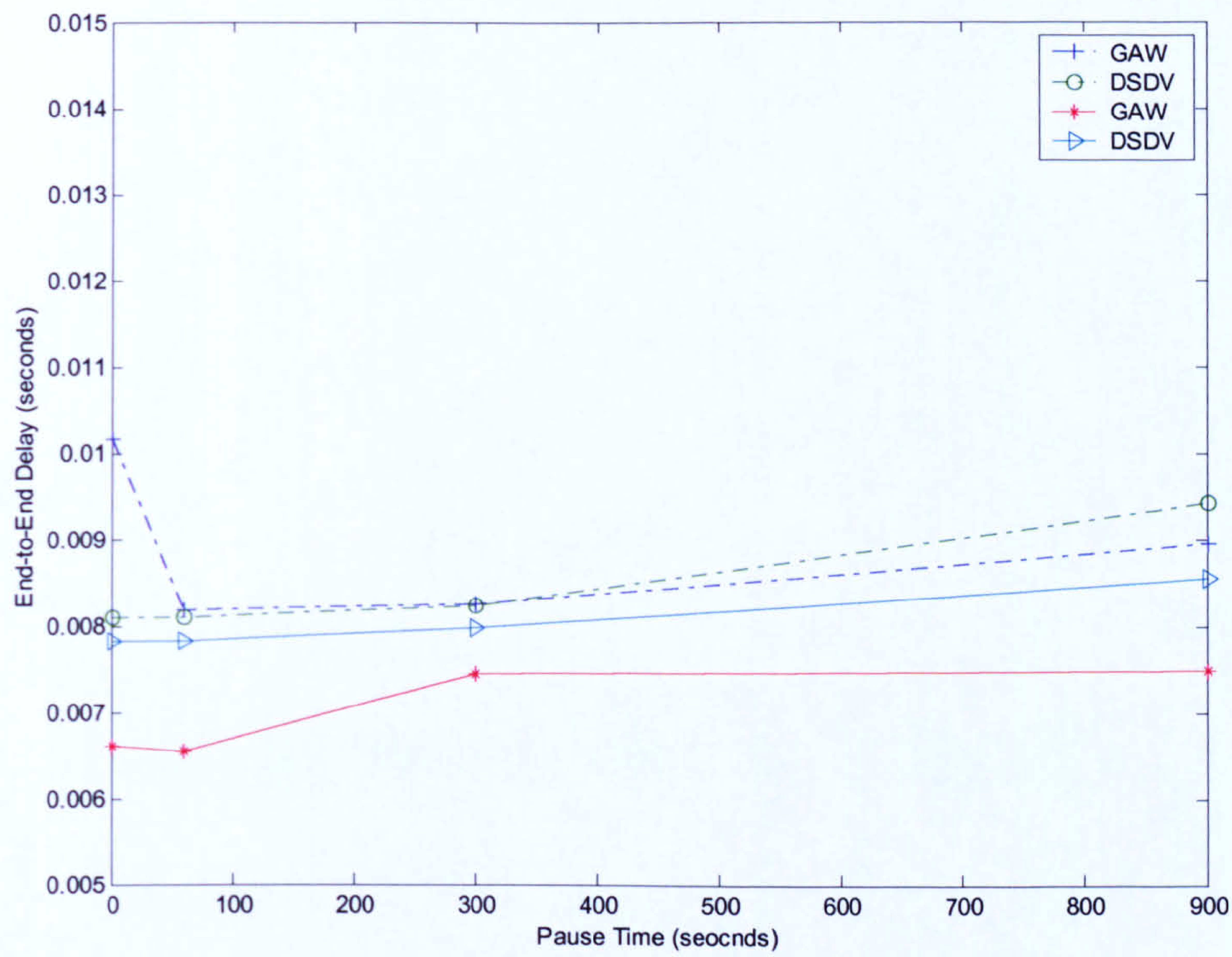



*Figure 5.39 Average End-to-End Delay time comparisons for IG at (200,100)*

### *D. Performance comparison with IG at (450,150)*

Having examined the MANET to Internet performance of GAW and *DSDV* when the IG is in the middle of the wireless network, this section investigates the situation with inverse communication. Figures 5.40-5.42 show that for the packet delivery ratio, both GAW and *DSDV* again performed better with the sources on the Internet. The reason is that which has been explained in A, namely queuing before a route is available. However, since the original packet delivery ratio is very high, above 99%, end-to-end delay time does not change significantly, and the routing overhead remains the same.

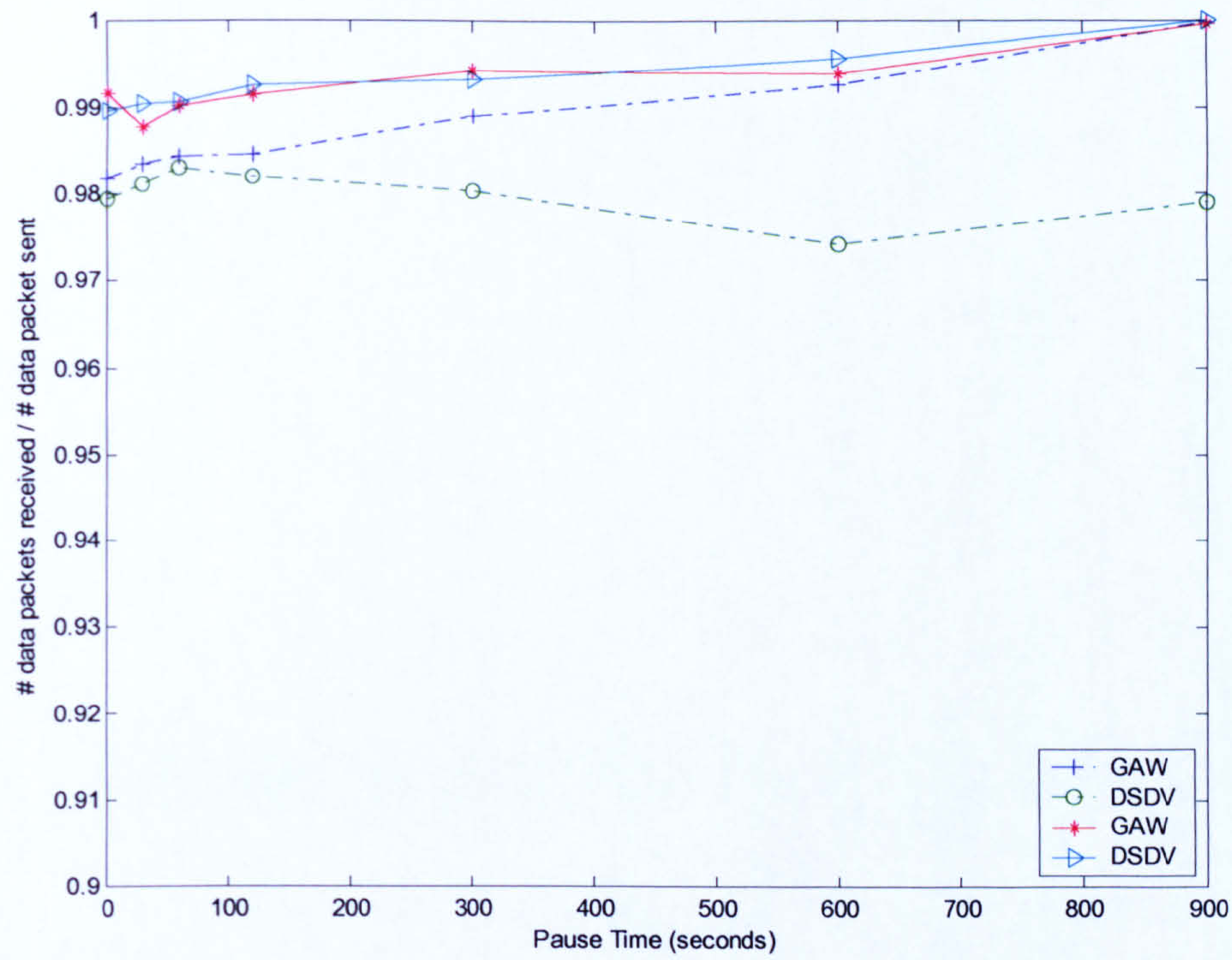



*Figure 5.40 Packet delivery ratio comparisons for IG at (450,150)*

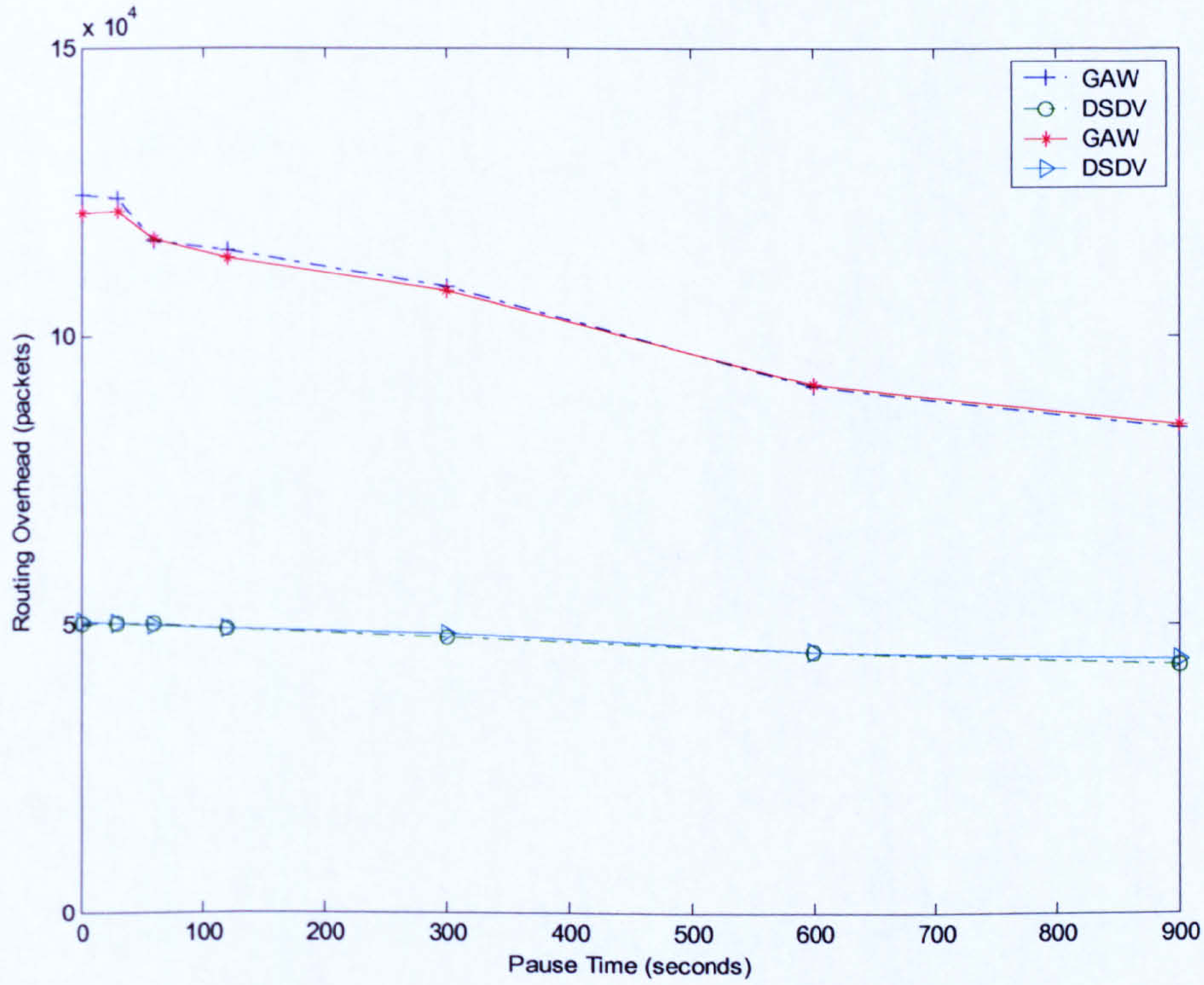



*Figure 5.41 Routing overhead comparisons for IG at (450,150)*

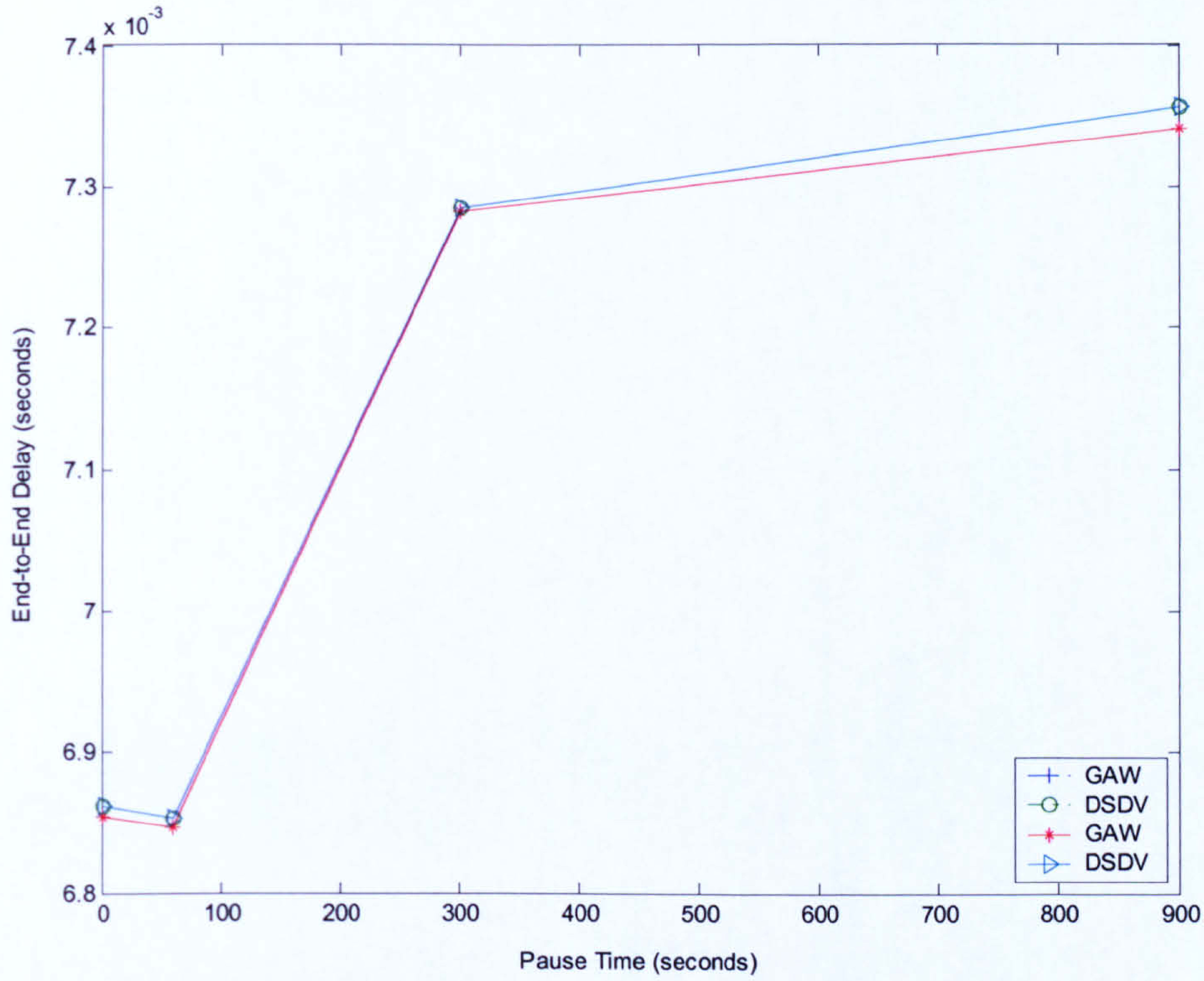



*Figure 5.42 Average End-to-End Delay time comparisons for IG at (450,150)*

## 5.5.4 Conclusion

### *A. IG's Broadcast Interval*

The IG's broadcast interval does not show any effects to either GAW or *DSDV* for Internet to MANET communication. In fact, the routes to the MANET on the IG were updated by the MANET routing protocols so the performances are not affected by the IG discovery method used.

### *B. Overall Performance*

The overall performance of the Internet to MANET communication of GAW and *DSDV* were compared with the MANET to Internet communication. Considering the different routing algorithms used by these two communications, it is clear that their performances are not symmetric. The packet delivery ratio was improved by queuing the packets before a route is available while a delay was expected. However, the delays were not significant when the IG was moved into the middle of the simulation network. A significant contribution in this section is that the nodes on the Internet can discover the destinations in the MANET without sending out any probing message into it. As a result of this, the simulations showed that no changes were made to the routing overhead in the MANET.

## 5.6 Extended Wireless Communication

This section covers the extended wireless communication using the GAW routing method. As discussed in section 4.3.7, extended wireless communication makes the wireless->wired->wireless communication possible. Since the extended wireless communication is only involved when the route discovery has failed in the wireless network, it can be demonstrated by a mixed MANET and Internet communication. In this section, the results of the simulation of normal MANET communication will first be shown in section 5.6.1. In section 5.6.2, simulations will be undertaken to investigate the case of extended wireless communication.

### 5.6.1 Normal Ad Hoc Wireless Communication

*A. Simulation Setup*

The simulations shown in this subsection used the same 70 scenario files but with the IG removed. All communications were carried out between wireless nodes using Ad Hoc routing protocols. AODV, DSDV and GAW were used for pure Ad Hoc routing. There were 10 sources and 10 destinations randomly selected from the 30 wireless nodes.

***B. Results***

As shown in Figures 5.43 – 5.45, in the MANET, AODV had a better packet delivery ratio and less routing overhead than DSDV and GAW. Since GAW is derived from DSDV, they have the same routing algorithm in the MANET so that their results were very close. The difference between GAW and DSDV in Ad Hoc routing is that GAW has a shorter broken link timer which has been discussed in section 5.2.3, resulting in more routing overheads. The comparison of Ad Hoc routing protocols including AODV and DSDV can be found in [108].

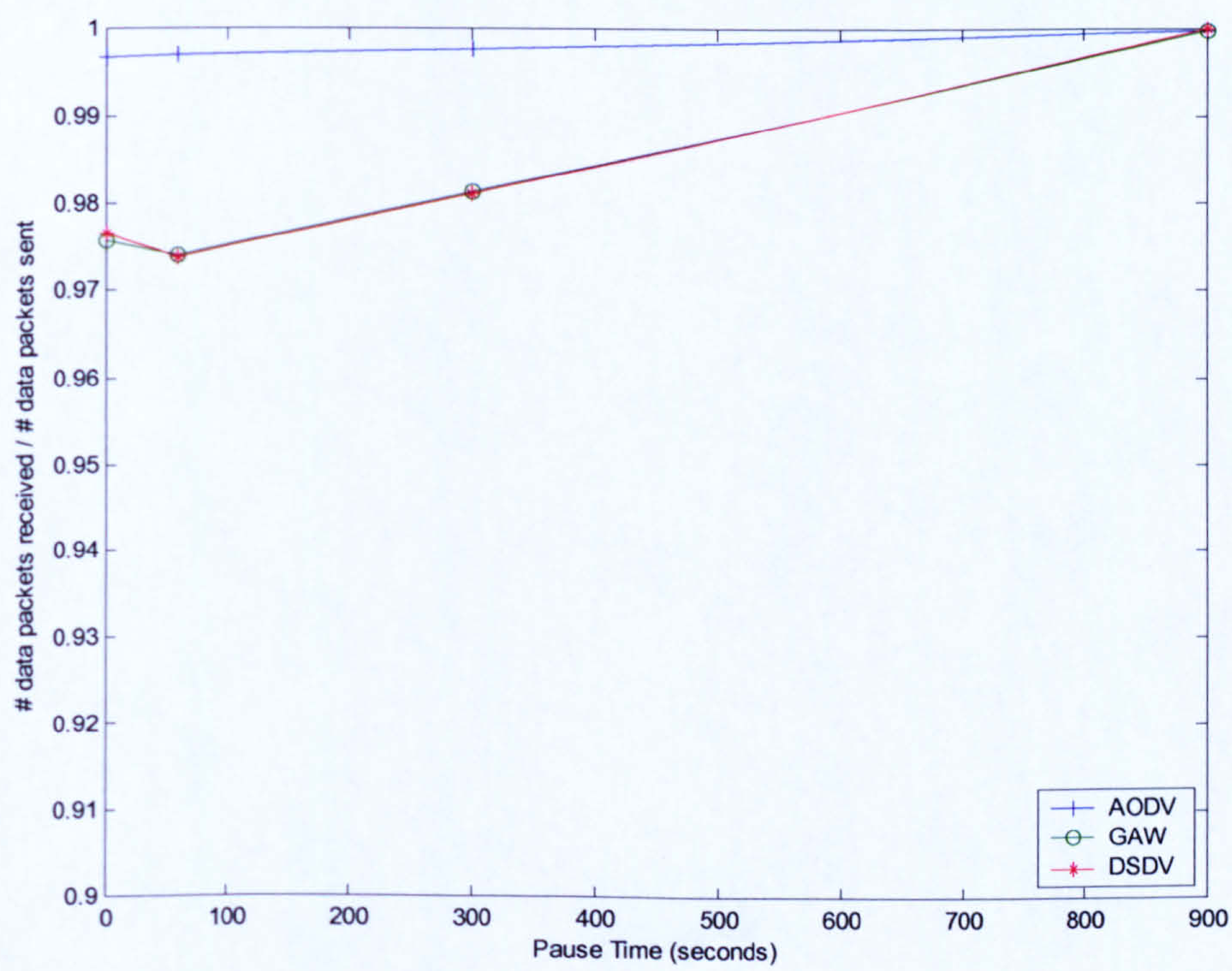



*Figure 5.43 Packet delivery ratio of AODV, GAW and DSDV in MANET*

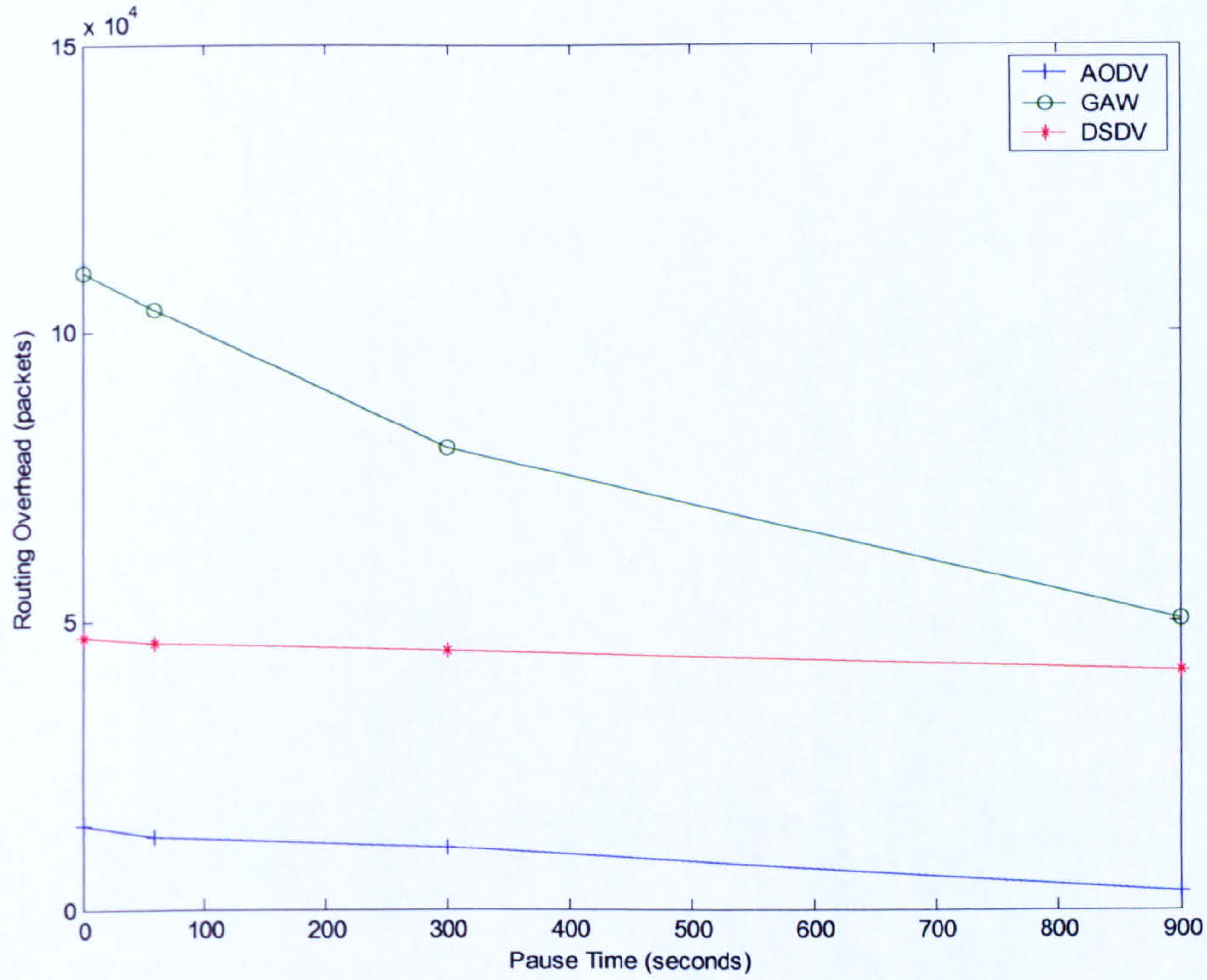



*Figure 5.44 Routing overhead of AODV, GAW and DSDV in MANET*

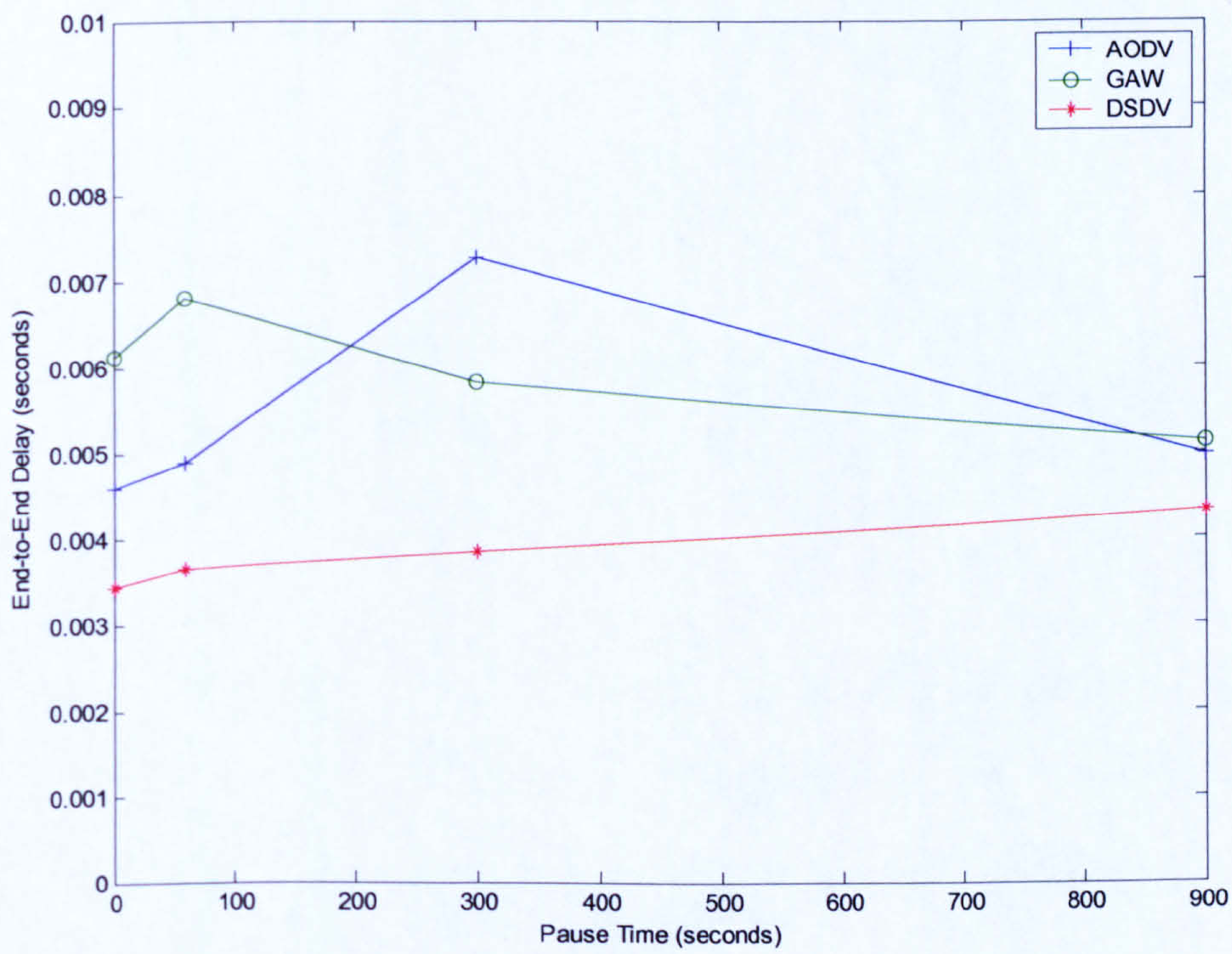



*Figure 5.45 Average End-to-End Delay time of AODV, GAW and DSDV in MANET*

### 5.6.2 Demonstration for Extended Wireless Communication

*A. Simulation Setup*

*Table 5.9 Simulation setup*

| Parameter | Value |
|---|---|
| Topology Size | 900m X 300m |
| Wireless Transmission Range | 250m |
| Number of Wireless Nodes | 6 |
| Number of Wired Nodes | 3 |
| Number of IG | 1 |
| IG Position | (450,150) |
| Traffic Type | Constant Bit Rate |
| Packet Rate | 1 Packet / Second |
| Packet Size | 64 Byte |
| Source -> Destination | Node 3 -> 6 start at 150.55<br>Node 8 -> 7 start at 200.36 |

*Table 5.10 Node's Positions and Movements*

| Node | Position |
|---|---|
| 3 | (250,150) |
| 4 | (350,50) |
| 5 | (550,50) |
| 6 | (550,200) |
| 7 | (750,50) |
| 8 | (100,50) |
| **Movement** | |
| At 300.00 seconds Node 4 move from (350,50) to (150,0) at 10m/s | |
| At 600.00 seconds Node 4 move from (150,0) to (350,50) at 10m/s | |

Figure 5.46 shows the simulation scenario for extended wireless communication. To demonstrate, the network topology and node's movement has been specially designed that the IG presented with broadcast interval at 10 seconds. Table 5.9 and 5.10 show the scenario setup and node's movement. In the simulation, the links between sources and destination were available until at 300 seconds, node 4 moves away resulting in a broken wireless link between the two groups. At 600 seconds, node 4 moves back to the original position to restore the wireless link.

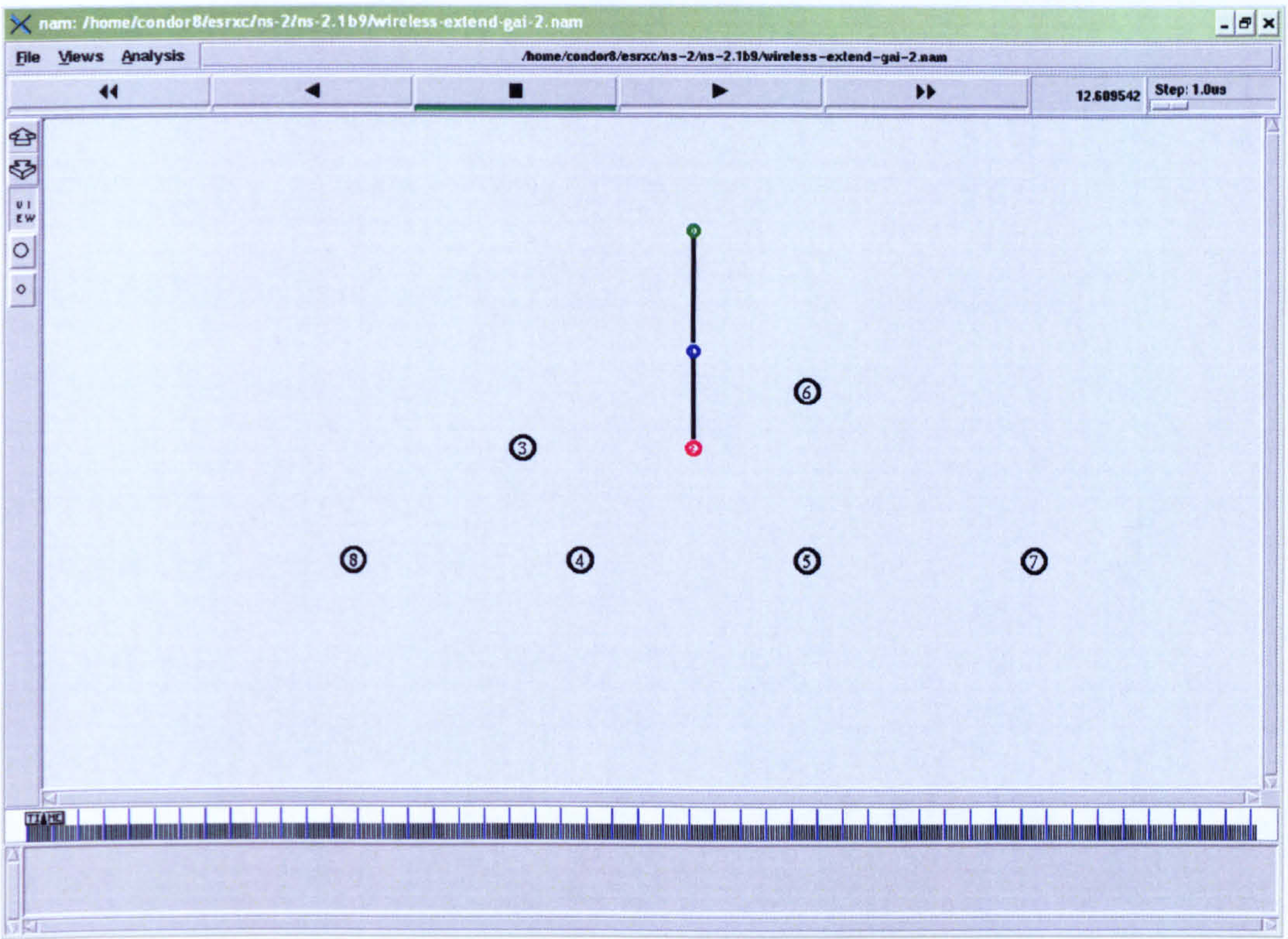



*Figure 5.46 Extended wireless communication simulation scenarios*

### *B. Simulation Results*

*Table 5.11 Simulation Results*

| Protocols | Packet Delivered | | Packet Dropped | Routing Overhead |
|---|---|---|---|---|
| | Links | Number | | |
| AODV | Wireless | 928 | 622 | 477 |
| DSDV | Wireless | 962 | 588 | 1047 |
| GAW | Wireless | 962 | 4 | 1515 |
| | Wireless->IG->Wireless | 584 | | |

The simulation results are shown in Table 5.11. During the simulation period, there were a total of 1550 packets sent by the sources. AODV and *DSDV* used only wireless links, so when the broken link between 4 and 5 occurred and no alternative wireless links were available, all the packets were dropped. However, the GAW routing method managed to use the extended wireless communication by forwarding packets to the IG. Due to the fact that the wireless node needs to ensure that no wireless links are available before switching to extended communication, although the IG routing information is already in the routing table. As it shown that some packets were still dropped when the wireless link was broken. The maximum broken link detection time in the GAW routing method is 15 seconds. The result in this simulation shows that only 4 packets were dropped. However, this simulation only set out to demonstrate the extended wireless communication for GAW routing method. A detail analysis of how the extended wireless communication affects the mixed MANET and Internet communication is shown in section 5.6.3.

### 5.6.3 Simulations for Extended Wireless Communications

*A. Simulation Setup*

*Table 5.12 Simulation Setup*

| Parameter | Value |
|---|---|
| Topology Size | 900m X 300m |
| Wireless Transmission Range | 250m |
| Number of Wireless Nodes | 10 |
| Number of Wired Nodes | 3 |
| Number of IG | 1 |
| IG Position | (450,150) |
| Sources | 5 randomly selected |
| Destinations | 5 randomly selected |
| Traffic Type | Constant Bit Rate |
| Packet Rate | 1 Packet / Second |
| Packet Size | 64 Byte |
| Source Start Time | Between 100 to 20 seconds |

To simulate the extended wireless communications, the scenarios have to be chosen with fewer node densities so that the routes may be easily lost in the wireless topology. Using the scenario generator, 40 scenarios were generated with 10 wireless nodes at pause times of 0, 60, 300 and 900. The nodes' movement were 'random waypoints' at a maximum speed of 1m/s. Again the wired network has 3 nodes and one of them is the IG with the IG's broadcast interval set to be 10 seconds. The simulation setup is shown in Table 5.12.

***B. Simulation Results***

The performance of extended wireless communications are shown in the Figures 5.47-5.49. Among the routing protocols used, AODV used the reactive routing method to probe the routes, and can achieve very high packet delivery ratios; unless the routes are physically broken. Both DSDV and GAW use routing tables so that the packet dropping may happen due to out dated routing information. However, if the broken links were confirmed, the GAW routing method can use the extended wireless routing method to discover the routes through the IG.

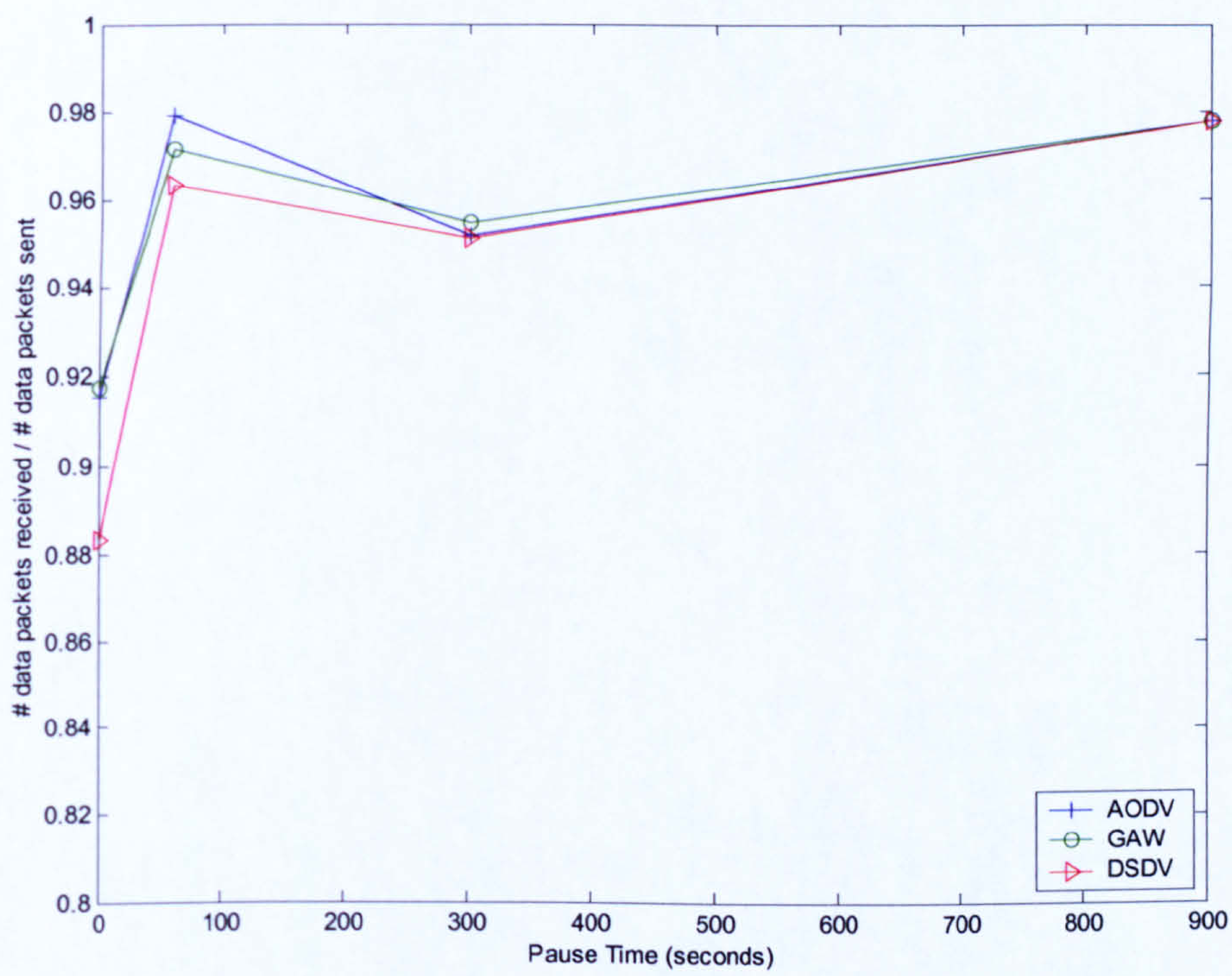



*Figure 5.47 Packet delivery ratio for extended wireless communications*

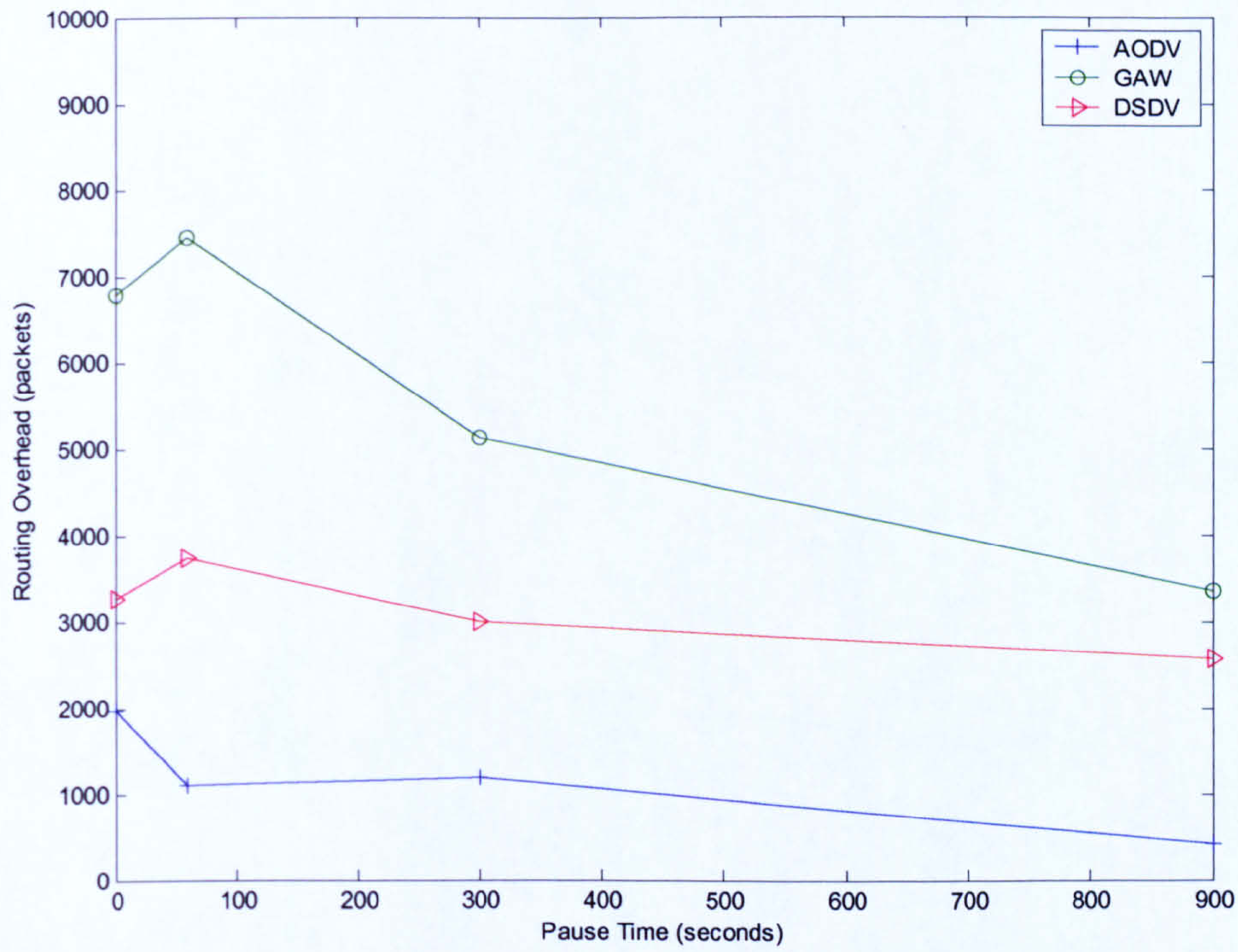



*Figure 5.48 Routing overhead of extended wireless communications*

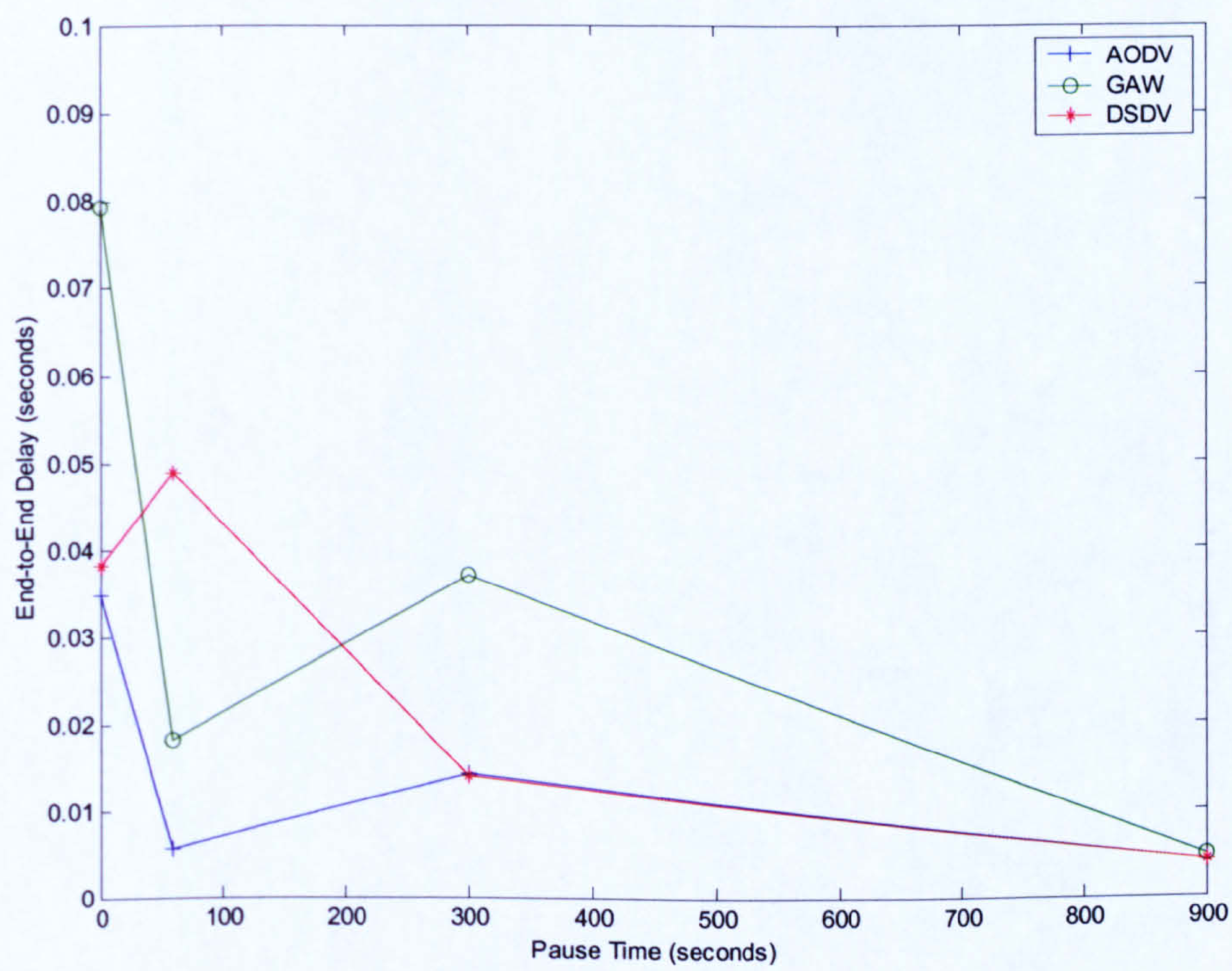



*Figure 5.49 Average delay time of extended wireless communications*

Working as table driven routing protocols, both GAW and DSDV may fail to find routes to destinations, which are still physical available, due to the slow response to changes of network topologies. This disadvantage is more obvious when the node's mobility is high. In contrast, AODV uses reactive routing protocols to discover the routes so that the routes that failed to be picked up by GAW and DSDV in MANET are still available. Figure 5.47 shows the difference between AODV and DSDV due to this reason. However, the GAW routing method can discover the routes through the Internet if they were not available in MANET. As a result, the packet delivery ratio of GAW is higher than DSDV and sometimes better than AODV. Consider the results in section 5.3, GAW routing method did not perform better than DSDV in a pure MANET environment. Therefore, the reason for this result is that the packets, which failed to be delivered by DSDV, were delivered in GAW routing method through extended wireless communication. Furthermore, AODV would definitely fail to deliver packets when the link was physically broken. When these packets found the routes through the Internet by the GAW routing method, the performance of GAW appears to be better than AODV.

The routing overhead of GAW is higher than the other two since it uses both the IG's broadcast messages and GAW update messages. With some packets taking longer routes through the Internet, the packets delay time of GAW is also higher than the other two.

### 5.6.4 Conclusion

This section shows the application of extended wireless communication in the GAW routing method. Developed on the successful connection between MANET and Internet, the extended route discovery in the GAW routing method enables the node searching for the destinations through the Internet if they are not reachable in the MANET. As a result, the packet delivery ratio was improved compared with DSDV. The application of this new form of extended wireless communication can be used to enhance the usual MANET communication and provide a great flexibility for future development.

# Chapter 6 Conclusions and Future Work



## 6.1 Overview

Wireless technologies have changed people's way of communication and extended communication into many areas, which was not possible before. MANET as an implementation has become more and more popular in many applications. As an extension for a stand alone MANET, the Internet connection for such a network is discussed in this thesis, and is developed via the new concept of GAW. The GAW routing method considered the special features of MANET, offering a way of Internet connection with both the wireless network's independency and Internet connectivity.

This chapter summarises the various aspects of the implemented GAW routing method from previous chapters and introduces the possible development direction for further research work. In section 6.2, the components of the GAW routing methods are connected together and the overall performance for communications between MANET and Internet are analysed. The possible research directions for GAW routing technology in MANET are introduced in section 6.3. In particular, the method combining both a routing and an addressing scheme for MANETs is explained.

## 6.2 Performance of GAW Routing Method

The desire for wireless life style has driven this research work to extend the Ad Hoc Wireless Network into Internet. Based on the concept of GAW, the routing method described in this thesis supports communication between MANET and Internet in both directions. The functions of GAWNs are defined to achieve the design goal.

*A. MANET to Internet Communication*

In the GAW routing method, the Internet connection process has been defined in two steps, routing within the Ad Hoc Wireless Network to GAWNs and communications between GAWNs and the Internet nodes. Before the desired packets reach the GAWNs, they are still in the Ad Hoc domain so that everything remains the same as in the normal Ad Hoc routing process except the destinations are the layer of GAWNs rather than single wireless nodes. Upon arriving at the GAWNs, packets are forwarded to the Internet as the second step of the Internet connection.

As discussed in section 5.2, the GAW routing method stops the flooding from IG's broadcast messages whilst maintaining a robust and stable MANET to Internet connection. The GAW route update and route selection scheme was designed to support such a connection. The GAW route update method offers a good response to the Internet connection changes with varying update messages. The GAW state classifies the GAWNs according to their connection availabilities. The route selection scheme from multiple GAWNs maximises the connection options and avoid errors caused by a single inaccurate route update. Both components work together to ensure routing efficiency and accuracy.

Any changes between GAWNs and the Internet, which cause GAW state changes, will be sent to the MANET by update messages. In particular, the GAW identification and cancellation messages are used to convert nodes between GAWNs and normal nodes. The results in Chapter 5 show that although the majority of the routing overhead of the GAW routing method still comes from the periodic update messages, the update messages related to GAWNs increase the overhead to achieve an improved packet delivery ratio.

A scheme used to improve the routing efficiency in the GAW routing method is load-balancing. Since the GAWNs are the final hops on the routes to the Internet, they are frequently used to forward route discovery packets and data packets. It is clear that no matter what routing methods are used, table driven or on demand, the loads on GAWNs will become heavier than others when more and more requests to the Internet are made from the MANET. The GAW routing method is implemented with the load-balancing scheme trying to uniformly distribute the load over all the available GAWNs. This simple load-balancing scheme is a benefit derived from the definition of GAWNs, which enables multi-route selection to the IG resulting in packet balancing between GAWNs. As shown in section 5.4.4, the load-balancing scheme working together with other GAW routing functions managed to provide effective route selection.

*B. Internet to MANET Communication*

With the data registration between GAWNs and the Internet, the communication from Internet to MANET becomes possible with the GAW routing method. This function enables the GAWNs to update all the destinations in their routing table to the Internet through normal route update messages. Without involving every individual node, members of the wireless network are known by the nodes on Internet. As the simulation results in section 5.5 show, nodes on the Internet get the routes to the destinations in MANET through GAWNs.

Currently the Internet to MANET communication is still a new area with lots of undiscovered issues, such as QoS routing and address autoconfiguration. The method used in this thesis simply extends the GAW route update into a registration form between GAWNs and the Internet. Without sending any additional information to the MANET, nodes on the Internet obtain and update routes to all reachable wireless nodes.

*C. The Extended MANET Communication*

The performance of the GAW routing method in MANETs is discussed in section 5.6. When no Internet connection is available, it basically uses the DSDV in Ad Hoc routing. In addition, the GAW routing method provides extended route discovery for wireless destinations through GAWNs, if the Internet connection can be found.

This extended MANET communication combines the two-way communication between MANET and the Internet. Through the registration from various GAWNs, the Internet nodes optimise the routing information. However, to keep the independency of the MANET, IGs do not send back routing information.

Therefore, it is possible that the routes to an unreachable wireless destination in MANET can be found through the help of the Internet.

In the GAW routing method, the packets destined for unknown wireless destinations can be forwarded to the GAWNs as the border layer to the Internet. Their destinations continue to be searched for with the possible route of wireless->wired->wireless. The simulations in section 5.6.3 show the application of extended route discovery through IG, with the necessary cooperation of a wired routing protocol plus further development of routing and addressing.

## 6.3 Future Work

The GAW routing method introduced in this thesis proposed a solution for the Internet connection for MANETs. The method is based on the concept of GAWNs, which created a new way of thinking regarding the relation between the Internet and MANET. There are also many other related aspects that can gain benefit from the concept of GAWNs. Especially, since the cross layer design of Ad Hoc Wireless Network allows [80, 82] GAWNs to find further application areas. This section introduces these areas as the direction for future development based on the method introduced in this thesis.

### 6.3.1 Further development for GAW Routing Method

*A. Extended Route Selection*

In the current GAW routing method, an extended route discovery scheme is used for unknown wireless destinations and finds the route through the Internet. This scheme takes advantage of the MANET to Internet connection and broadens the route discovery between different networks. However, the routes in the wireless domain have the higher priority since the alternative routes on Internet are only used when no routes in the wireless domain are available. If this scheme can be used as an alternative route discovery for normal routing, it will benefit the MANETs to optimise their available resources. For example, considering that routing in a MANET may consume the power of all the intermediate nodes, it may be worth thinking about using the routes on the Internet as a way to save the energy.

To add the route through the Internet into the normal route selection scheme, some modification of the registration between GAWNs and the Internet needs to be done. From the route update point of view, unlike the current registration method between GAWNs and the Internet, the IGs need to send back routing information as well. All wireless destinations in the IG's routing table are sent to the MANET. Upon receiving this routing information, wireless nodes need to make another table for these routes as a backup for the currently maintained route.

The route selection scheme needs to be developed further also. When the destination is out of the routing table of the source node, a normal extended route discovery is applied if it can be found in the backup routing table. If the destination exists in both tables, a comparison is carried out. This comparison can be based on the distance or other metrics such as energy. By examining the power consumption of each route, the extended route selection can be used not just as a backup routing scheme but as a way to improve the routing efficiency. One way to do this is to consider a threshold for the power consumption in delivering the packets in the wireless domain. Any route above this value can be assumed to be an unknown destination for which the extended route selection scheme is called.

*B. Quality of Service for Internet Connection*

The load-balancing scheme in the GAW routing method provides the basis for route distribution among the GAWNs. The Quality of Service (QoS) for Ad Hoc Wireless Networks is still a large topic to explore, since the Internet and MANETs have different environments in supporting the QoS for data communication. GAWNs provide the interface for IGs' to probe the wireless network without going into it, which offers a platform to gather the wireless network's information. On the other hand, apart from the routing information, GAWNs can send data related to the QoS requirements to the IGs. Further developments to improve the QoS for communications between MANET and Internet could prove fruitful.

### 6.3.2 GAW for Address AutoConfiguration

*A. Why is Address Autoconfiguration Necessary?*

As the GAW routing method is used to provide the Internet connections for wireless nodes in MANETs, the addressing issues need to be considered as well. In the simulations in Chapter 5, every wireless node uses a unique IP address. However, in some applications, wireless nodes may need to change their IP addresses when they join another wireless domain if there is an address conflict, when the address autoconfiguration is needed. It is also required when wireless nodes gain connections to the Internet but cannot keep their own IP address for the communication purposes.

The address autoconfiguration for MANET as a new research area has drawn more attentions from researcher [116, 117]. Currently, some address protocols give the solution for address autoconfiguration, such as IPv6 address autoconfiguration [118] and mobile IP [71]. They are based on IP and provide a flexible solution for mobile users who move from one network to another. However, a MANET user may not have direct contact with the IG and it is hard to directly apply IPv6 or mobile IP to manage the address of such a network.

The address autoconfiguration method associated with the GAW routing method can be used to classify the configuration process into more specific and event oriented steps. This section will introduce the concept for future development.

***B. How Can GAW Address Autoconfiguration Work?***

The idea of GAW address autoconfiguration is shown in Figure 6.1. Generally speaking, the GAWNs in the routing table of each wireless node are used as references when an address conflict happens. In theory, the nodes with a conflicting address should have different routing table members. As a result, the GAWNs' references can be used in the Duplicate Address Detection (DAD) process to find an address conflict.

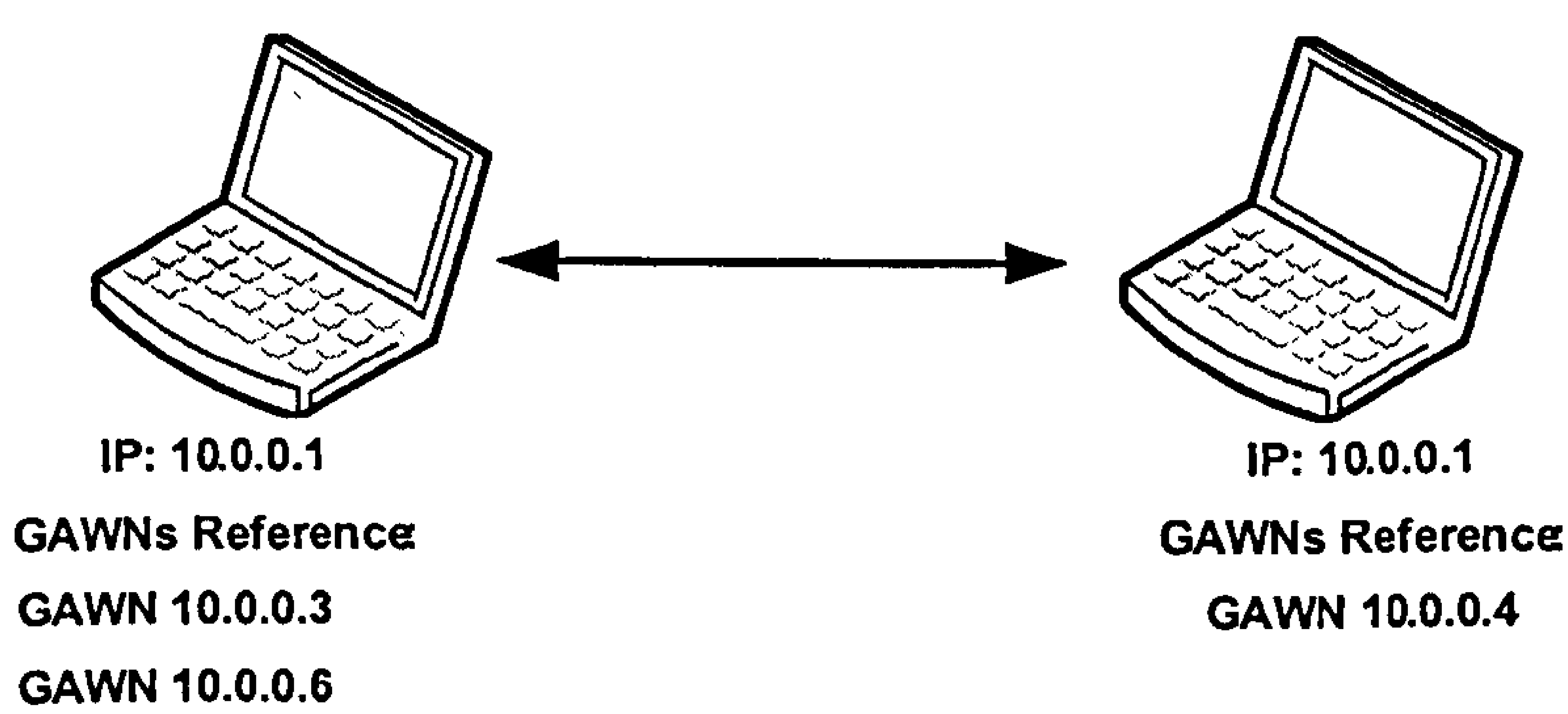



*Figure 6.1 How GAWN Reference Work Where Address Conflict Happens*

The DAD is carried out with the normal route update process. As the node moves into another network, it broadcasts the current address and route information to the network's members. All nodes in the network analyse the data received from their neighbours and start the address autoconfiguration when there is a conflict. According to the GAWNs' references, the wireless node's movements and its address autoconfiguration process are catalogued into 4 scenarios, shown in Figure 6.2.

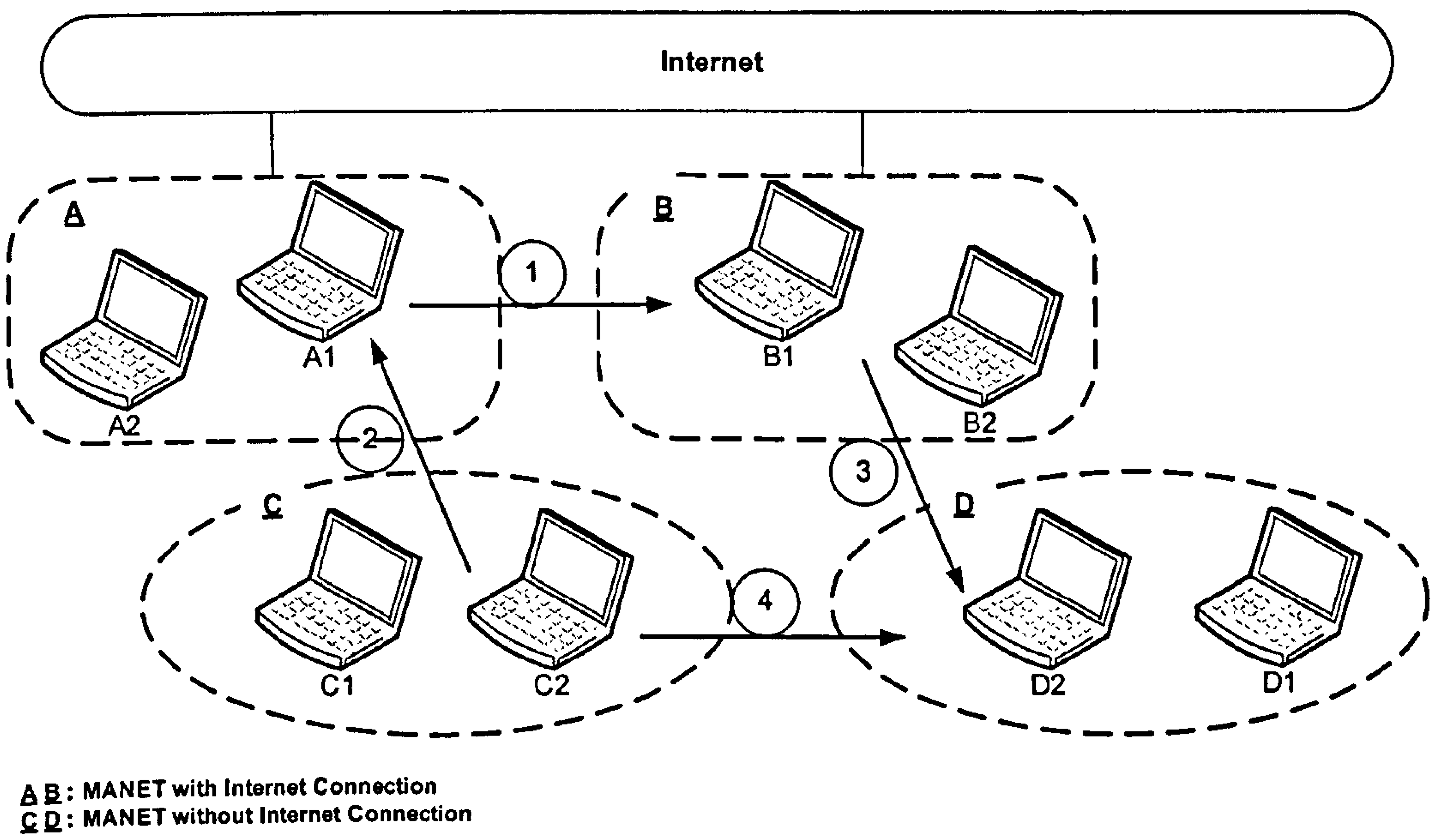



*Figure 6.2 4 Scenarios for GAW Address Autocofiguration*

The 1st case shows the conflict when it occurs between members of two MANET with Internet connection. In this case, the conflict pair should sort out their addresses depending on the wired network's address configuration protocols. Nevertheless, they can still use the GAW references to make them distinguished. The 2nd and 3rd case show the conflict between members with and without Internet connection. In these cases, the GAW references are the obvious difference between them. The 4th case is the normal address autoconfiguration between MANET members. Since the GAW reference cannot help in this case, any other method can be used.

After the new address has been accepted in the new network, a message will be sent back to the original network to inform it of this change, providing the link can be found.

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